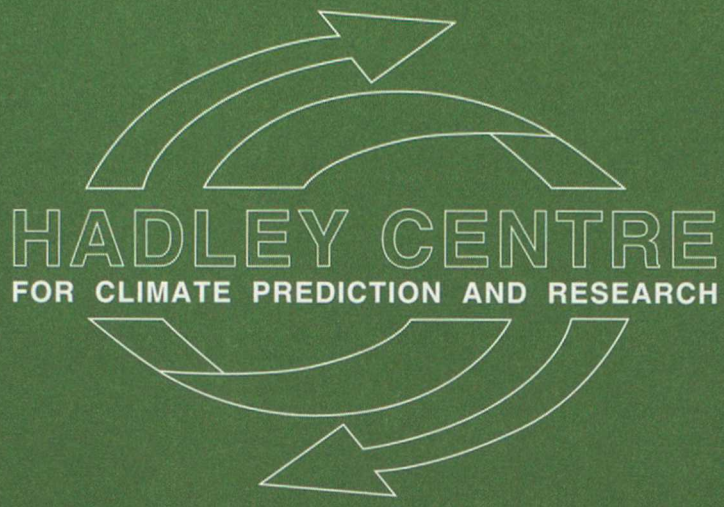

The sensitivity of climate simulations to the specification of mixed phase clouds

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THE SENSITIVITY OF CLIMATE SIMULATIONS TO THE SPECIFICATION OF MIXED PHASE CLOUDS

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The Sensitivity of Climate Simulations to the Specification of Mixed Phase Clouds.

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ABSTRACT

In the prognostic stratiform cloud scheme used in the UK Met. Office Unified Model, mixed phase clouds are assumed to exist between 0 and -15°C. Recent observations of such clouds, carried out using the C-130 aircraft of the Met. Research Flight, suggest that a smaller range of 0 to -9°C may be more appropriate. The sensitivity of cloud and radiation fields as simulated by a 5x7.5° latitude-longitude version of the Unified Model to such a reduction in the temperature range of mixed phase clouds is considered. Using a smaller temperature range systematic errors in the radiation budget of the model are reduced in mid-latitudes, bringing the model into closer agreement with ERBE data. The sensitivity of model albedo to an increase in the temperature range over which mixed phase clouds are assumed to exist, suggested by previous observational studies, is also considered together with the impact of removing the mixed phase part of the precipitation parametrization altogether.

1. INTRODUCTION

Although it is clear that clouds warm the atmosphere through condensational heating, the net effect of their interaction with radiation is less easy to define and quantify. The two opposing effects are similar in magnitude and different clouds have different effects . Recent results from satellite observations (Ramanathan et al 1989) suggest that the net effect of clouds is to cool the climate system with a magnitude of 10-20Wm^{-2}, with the cooling due to the reflection of short wave radiation being 40-50Wm^{-2} and warming due to long wave heating around 30Wm^{-2}. With the radiative forcing of the atmosphere due to a doubling of carbon dioxide being only 4Wm^{-2} it is clear that small changes in cloud forcing can have large climatic impacts. Hence the need for accurate specifications of cloud processes in general circulation models used in climate change research.

The above factors, together with a desire to have improved precipitation forecasts in NWP models, have led to the introduction of more complex stratiform cloud parametrizations in the current generation of global models (for example Sundqvist (1978), Smith (1990), Tiedtke (1993)). In these cloud cover and condensed water contents are predicted, allowing cloud radiative properties to be calculated interactively rather than being prescribed as in the scheme of Slingo (1989) used in the Met. Office Unified Model. However even with these advances the representation of clouds in climate models still remains an area of great uncertainty.

This is well illustrated by the work of Senior and Mitchell (1993) in which they studied the

sensitivity of the equilibrium response of a climate model to a doubling of carbon dioxide to changes in the stratiform cloud scheme. With a relative humidity scheme (Mitchell and Ingram 1992) the global mean temperature response at equilibrium was 5.4K but reduced to 3.3K when the prognostic cloud scheme of Smith (1990) was used. In their conclusions they suggest that "reduction in the current range of uncertainty will require an improved knowledge of cloud microphysical properties, which will only be obtained through carefully planned field studies".

One area of uncertainty in current GCM cloud parametrizations is the estimation of precipitation from clouds in the temperature range in which patches of ice and water are observed to exist within the same cloud layer, so called "mixed phase clouds". A previous study by Li and Le Treut (1993) using the LMD GCM, with a prognostic cloud scheme similar to that of Smith (1990), suggests that the sensitivity of modelled climate to a ±2K change in sea surface temperature is highly dependent upon the specification of the temperature at which cloud condensate was treated as ice (varying between 0 and -15°C in these experiments). Given the uncertainty in estimates of climate change from GCMs due to the specification of ice precipitation that this study suggests, it would seem essential that more observationally based parametrizations of mixed phase cloud be developed.

This paper attempts to do so, using observations made by the C-130 aircraft of the Met. Research Flight (MRF) of mixed phase clouds (Moss and Johnson 1993) to refine the ratio of ice to water content within mixed phase clouds assumed by the stratiform cloud

parametrization of Smith (1990). The scheme and observations are described in section 2. Results from tests of the revised scheme in a low resolution (5x7.5° latitude-longitude) version of the Met. Office Unified Model (used as the Hadley Centre Climate Model) are presented in section 3, showing an improved present day radiation budget simulation. Comments are made in section 4 regarding the effect of the revised parametrization upon the sensitivity of the model to an increase in greenhouse gases.

2. MODEL DESCRIPTION

(a) The Unified Forecast/Climate Model

The model used in this study is the Hadley Centre Climate Model (a version of the UK Met. Office Unified Model described by Cullen (1993)). In part this is a development of the model used by Senior and Mitchell (1993), being of a grid-point type with 19 (irregularly spaced) levels in the vertical using a hybrid sigma/pressure co-ordinate. A conservative split-explicit integration scheme is used (Cullen and Davies 1991), and cloud water and ice are included as prognostic variables.

The annual cycle of radiation is imposed on the model which employs an interactive radiation scheme (Ingram 1993) incorporating the short wave cloud optical property scheme of Slingo (1989) using cloud water contents predicted by the cloud scheme of Smith (1990, 1994). The

radiation scheme is called every 3 hours in order to represent the diurnal cycle but the incoming solar flux is updated every time step to avoid discontinuities in surface properties. The boundary layer scheme is formulated in terms of conserved variables and so can represent both dry and cloudy boundary layers. It also includes a representation of non-local mixing (Smith 1994). Mixing coefficients are stability dependent, using a moist Richardson number. A mass-flux convection scheme with stability dependent closure (Gregory and Rowntree 1990) is included which includes a representation of deep convective downdraughts (Gregory and Allen 1991). Surface hydrology and a soil temperature model are also included (Warrilow et al (1986), Dolman and Gregory (1992)). Mean orography is used together with the gravity wave drag scheme of Palmer et al (1986), although this has been modified to limit orographic variance through consideration of the Froude number of the flow rather than by constraining it to be less than a maximum value (Wilson and Swinbank 1991).

The model is run at a variety of horizontal resolutions, transient coupled integrations being carried out at 2.5x3.75° latitude-longitude resolution with a time step of 30 minutes. Here a low resolution version of the model with half the horizontal resolution (5x7.5°) and a time step of 60 minutes is used. At its lower boundary the model is forced with climatologically varying sea surface temperatures. This model was designed for use in climate sensitivity experiments and its radiation budget and cloud fields are similar to the high resolution model. Figure 1 compares zonal mean top of atmosphere albedo from two parallel integrations of the model with the two horizontal resolutions discussed above for northern hemisphere summer (3 year means). Similar errors compared to ERBE data (a four year mean from 1985 to 1989)

are seen in both configurations of the model, with albedo being over estimated in the mid-latitudes of both hemispheres by up to 10%.

(b) Stratiform cloud scheme and representation of Mixed Phase cloud.

The Unified Model employs the prognostic cloud scheme of Smith (1990). In this, cloud cover and cloud condensed water amount within a grid box are predicted using a specified distribution of total water content within the grid box, the standard deviation of which is related to a critical relative humidity below which no cloud forms. The original microphysics scheme described by Smith (1990) has been modified to use a fully divergent form for ice fallout, rather than allowing all precipitating ice to fall to the ground within a single time step. The ice precipitation treatment has also been made fully implicit. Other modifications are discussed later and the revised scheme is described fully by Smith et al (1994).

A distinction is made between water and ice in the calculation of precipitation. In water cloud the available condensed water is spread over many cloud condensation nuclei (CCN) and only a few droplets are able to fall out (Pruppacher and Klett 1978). For ice clouds very few CCN act as ice nuclei (Heymsfield and Sabin 1989), and so the cloud ice is spread over fewer larger particles which are able to fall out of the cloud relatively quickly (Heymsfield, 1977). In the temperature range where mixed phase cloud occur (discussed in section 2d below) it is assumed that a fraction of the cloud condensate is liquid and a fraction ice, the exact proportion of water (f_L) being a function of temperature. Hence the grid box mean

cloud water and ice contents are given by,

$$q_w = f_L q_c$$
$$q_I = (1-f_L) q_c \qquad (1)$$

For water cloud the precipitation rate is given as,

$$\left(\frac{dq_w}{dt}\right) = -C\left(c_T\left[1-\exp\left(\frac{\rho q_c/C}{c_w}\right)^2\right] + \frac{P}{c_A}\right)\frac{q_w}{C} \qquad (2)$$

where C is the fractional cloud area, q_w is the grid box mean cloud liquid water, q_c the total cloud condensed water content, P is the precipitation (liquid or frozen) entering the layer from above and c_T, c_w and c_A are specified parameters.

Equation (2) is based upon the parametrization proposed by Sundqvist (1978) but with an additional accretion term added, increasing the conversion rate when precipitation falls into a layer (Golding 1986). The values for the parameters of equation (2) are;

$c_T = 10^{-4}$ s^{-1}

$c_w = 0.8\text{x}10^{-3}$ kg m^{-3} for land points,

$= 0.2\text{x}10^{-3}$ kg m^{-3} for sea points

$c_A = 1$ kg m^{-2}

The exponential term inhibits the formation of rain when the incloud condensed water density ($\rho q_c/C$) is small compared to c_w. The different values for c_w over land and sea reflect the observation that air over oceans has less CCN and so drops grow larger and precipitate more

easily.

For ice clouds the precipitation rate is given by,

$$(\frac{dq_I}{dt}) = (P_* - \rho q_I V_F)/\rho\delta z \qquad (3)$$

where P_* is the precipitation entering the top of the layer which is assumed to remain in the layer and V_F is the fall velocity of ice calculated using the formula derived from observations of cirrus clouds by Heymsfield (1977);

$$V_F = V_{FI}(\frac{\rho q_c / C}{c_F})^{0.17} \qquad (4)$$

with V_{FI} set to 1m/s and c_F to 1.01086×10^{-3} kgm^{-3}.

It has already been noted that the scheme described here differs from that of Smith(1990) in its calculation of ice precipitation rates. The treatment of precipitation from mixed phase clouds has also been modified. In the original formulation of Smith(1990) $q_w$was used in the exponential term of eqn (2), consistent with the interpretation that f_L describes the fraction of water in a cloud which is a homogeneous mixture of ice crystals and water drops. As a description of mixed phase clouds this is rather unphysical and contrary to observations. Because of the lower saturation vapour pressure of ice with respect to water, if a mixture of ice crystals and water droplets exist together, the ice crystals will grow rapidly at the expense of the water droplets making such a mixture a transitory phenomena. Using q_c in the exponential term of equation (2) and in equation (4) implies that f_L describes the horizontal

fraction of the cloud which is composed of liquid water.

A further difference of the scheme here from the original version is that cloud water and cloud ice are depleted separately with rates determined by equations (2) and (4) (Smith 1994). In the original version of the scheme an average cloud water depletion rate was calculated from equations (2) and (4) weighted by f_L. This was then used to deplete the total cloud water in the grid box, consistent with the interpretation of f_L assumed by the original scheme. However with the fully divergent form for ice fallout now used this resulted in a build up of ice towards the freezing level as more of the condensate was treated as water for the purposes of precipitation.

(c) Form of f_L

In the standard version of the Smith cloud scheme f_L is taken to be given by a quadratic spline varying from 1 at 0°C to 0 at -15°C (figure 2, solid curve). As remarked upon in the introduction, Smith (1990) states that "the form of the partitioning curve (f_L) and the lower bound of -15°C have no basis in observation or theory", being "chosen for simplicity and smoothness and the lower bound was chosen by 'tuning'. Excessive cloud was simulated if liquid water was assumed to exist below -15°C."

Moss and Johnson (1994) attempt to provide a better measure of the fraction of cloud which is water within the mixed phase region through the analysis of cloud water and ice

measurements with the C-130 research aircraft of the UK Met. Office Met. Research Flight (MRF). Figure 2 shows a scatter plot of the fraction of cloud water which is liquid as a function of temperature derived from measurements from mid-latitude frontal cloud in the eastern part of the north Atlantic. Also plotted is the linear fit to the data (dashed curve).

Although there is a high degree of scatter in the data the linear fit suggests total glaciation of cloud by -9°C rather than -15°C as in the standard precipitation scheme. The observations also show cloud ice present above 0°C probably due to fall out of ice from cloud below 0°C and also the fact that ice crystals melt when the wet bulb temperature exceeds 0°C rather than when the temperature exceeds 0°C as assumed in the Unified Model.

This comparison suggests that the mixed phase parametrization used in the precipitation scheme should be modified. As the Unified Model does not allow ice to exist above the freezing level a modification to the linear fit to Moss and Johnson's data is used as the basis of a revised parametrization, with full glaciation occurring at -9°C decreasing linearly to no ice at 0°C. The effect of this is that for temperatures from 0 to -15°C more of the cloud condensed water will be treated as ice in the estimation of precipitation. As ice fallout is unconstrained by a critical value of cloud ice content as in the rain parametrization, this will result in a faster depletion of cloud water within the region of mixed phase cloud. Fractional rates of depletion of cloud water given by equations (2) and (3) assuming total cloud cover, an air density of unity and no precipitation falling into the top of the cloud (figure 3), show that ice fall out is 10 times more efficient for a given cloud water content for a cloud layer

of 1000m depth. Hence it may be expected that the use of the revised mixed phase parametrization may result in reduced ice water contents in the mixed phase region.

3. IMPACT OF REVISED SCHEME UPON CLIMATE SIMULATION

Validation of cloud amounts and water contents simulated by general circulation models is difficult. Although satellite derived data sets of cloud amount are available, for example ISCCP (Rossow and Schiffer 1991), direct comparison to cloud amounts simulated by a climate model is difficult as the two estimates are derived using different methods; the former by inverting radiances, the later from thermodynamic considerations. Similar comments could be made concerning surface based estimates of cloud amount. An alternative method is to compare the model's simulation of the Earth's radiation budget, which is heavily influenced by the presence of clouds, with observed estimates. Here this method is used to provide an insight into the accuracy of the model's cloudiness and assess the sensitivity of the simulated radiation budget to the specification of mixed phase clouds.

Figure 4 shows estimates of the Earth's albedo obtained from ERBE satellite data, averaged between 1987 and 1991, while figure 5 presents the difference of model albedo from these observations for simulations with the standard and MRF mixed phase parametrization (both averaged over four years of integration). Using the standard mixed phase cloud scheme, during northern hemisphere summer (June/July/August - JJA), modelled albedos are found to

be excessive over northern Russia, northern Canada and Alaska and also over the north Pacific and Atlantic. In the southern hemisphere albedos are too large around 40S. With the introduction of the MRF mixed phase scheme many of these errors are reduced, bringing the model into better agreement with ERBE. Reductions in albedo are mainly confined to north of 60N and south of 45S, where significant cloud amounts exist in the lower troposphere (below 800mb) in the mixed phase region (see figure 7). During JJA albedos are reduced over Europe, Russia, Canada and Alaska. The largest albedo errors in this season, over the north Atlantic and Pacific south of 60N, are little affected by the change in parametrization. Low cloud in these regions is mostly not in the mixed phase temperature range and so is relatively unaffected by the change in the parametrization. In the southern hemisphere albedos are generally reduced south of 45S, although in some locations this leaves values below ERBE estimates (for example at 50S, 90E).

During northern hemisphere winter (December/January/February - DJF) albedo is again reduced over northern Europe and North America. The revised parametrization has a greater impact over the oceanic storm track regions of the northern hemisphere than during JJA, generally bringing the model into closer agreement with the observations, although in the north Atlantic the negative errors are more widespread. In the southern hemisphere an extensive region of excessive albedos is reduced south of 50S through the introduction of the MRF parametrization. This is again due to the largest layer cloud amounts being found in the lower troposphere in the temperature regime where the mixed phase cloud parametrization has an impact (see figure 7). Differences from observations are more negative south of 60S.

The general improvement in the simulated radiation budget of the mid-latitudes is confirmed when zonal mean albedo and top of atmosphere outgoing long wave radiation are considered (figure 6). Albedo is found to be lower in the mid-latitudes of both hemispheres, with the largest improvements coming in the summer seasons of both northern and southern hemispheres. These reductions in albedo generally bring the model closer to the ERBE estimates in these regions. Zonal mean outgoing long wave radiation is little changed through the use of the MRF parametrization, although small increases are found in the mid-latitudes of the northern hemisphere in JJA when the MRF parametrization is used.

Reductions in top of atmosphere albedo imply less negative short wave cloud forcing, from -60.1 to -58.6Wm^{-2} during JJA and -64.6 to -62.3Wm^{-2} in DJF on changing from the standard to MRF parametrization. However even with the revised parametrization values are still very different from ERBE estimates (-46.2 and -51.1Wm^{-2} for JJA and DJF respectively). Long wave cloud forcing is little affected by the change to the mixed phase cloud parametrization.

Changes in the top of atmosphere radiation budget can be caused by either modification of cloud optical properties or changes in cloud amount. Figure 7 shows zonal mean layer cloud amounts from the simulation with the standard mixed phase scheme and the difference in cloudiness which results from the introduction of the MRF mixed phase scheme with its reduced temperature range. Plotted also are the 0, -9 and -15°C mean isotherms from the standard simulation. Although the location of these will vary with time, these provide an indication as to where the mixed phase parametrization is being applied.

In mid-latitudes maximum zonal mean layer cloud amounts are found below 750mb in both hemispheres. The latitudinal extent of the mixed phase region at low levels tends to be broader in the summer hemisphere, especially during JJA. This may be the reason for the broader latitudinal range of albedo reductions seen in the summer hemispheres. However in the northern hemisphere during DJF, snow cover over land together with the lack of sunlight may partially mask changes in top of atmosphere albedo due to the change the mixed phase cloud representation. Reductions of up to 8% in zonal mean cloud amount are seen with the introduction of the modified parametrization (at 80N during JJA). Other changes to cloud amount are seen outside the mixed phase region, for example over the south pole. These are outside the mixed phase region and so changes are not a direct consequence of the modified parametrization.

These reductions in cloudiness result from the more efficient manner in which cloud ice can be removed from the model (see section 2b above). This is confirmed by figure 8 showing zonal mean total cloud water contents (grid box mean values, liquid plus ice) from the standard and modified integrations remaining after precipitation has been removed. Reductions in cloud condensed water are seen in the mixed phase region with the use of the MRF parametrization, values being up to 30% lower than in the standard integration (DJF 65N). Cloud water contents remain little changed outside of the mixed phase region, i.e. at temperatures above the freezing level and below -15°C. Reductions in cloud water content lead to smaller cloud water paths and therefore will also contribute to the changes in top of atmosphere albedo through the interactive cloud optical properties scheme used in the Unified

Model.

Changes in the top of atmosphere radiation budget can also result from changes in the optical properties of the cloud particles regardless of changes in cloud amount and liquid water path. The mixed phase cloud function "f_L" is used to estimate a weighted mean value of the effective radius of cloud particles in the mixed phase region assuming an effective radius of 7μm for water drops and 30μm for ice crystals. The change in its specification therefore affects the top of atmosphere albedo even if cloud amount and total cloud water content remain constant. Figure 9 compares zonal mean albedo for a single DJF and JJA from a 9 month experiment (starting on the 1st of December) in which the MRF mixed phase parametrization is used in the radiation scheme only. Also shown are equivalent single seasons for the two simulations discussed previously. Although internal variability makes interpretation difficult this experiments suggests that half of the reduction in albedo of the summer hemisphere comes from the change in specification of effective radius. Use of the MRF parametrization leads to a larger effective radius at a given temperature which implies a reduced single scattering albedo and so reduced planetary albedo.

4. DISCUSSION

The above results have indicated that simulations of present day climate are sensitive to the specification of the phase of precipitation processes in cloud. Changing the ad-hoc

parametrization used in the standard version of the Hadley Centre climate model to one based upon in-situ observations of such clouds improves the model's radiation budget in the mid-latitudes of both hemispheres. However considerable uncertainty still exists regarding the specification of mixed phase clouds.

As can be seen from figure 2 there is a wide spread in the observed relationship between the fraction of ice water and temperature. The best fit line presented by Moss and Johnson (1994) had only a correlation coefficient of 0.56 with the observations. Bower et al (1995) expands on the analysis of this data suggesting different parametrizations for continental and maritime clouds, the same ratio of water to total condensate amount being found at temperatures 1°C warmer in the latter compared to the former. The use of this modified parametrization is only likely to give small differences relative to the results presented above. However the suggestion of such an air mass contrast, together with the wide temperature spread in the observations, indicates that the use of the simple parametrization here based purely on ambient temperature may not be wholly appropriate.

It should also be noted that some cloud schemes used in large-scale models use a much wider temperature range to specify the presence of mixed phase clouds. For example the cloud scheme recently developed at ECMWF (Tiedtke 1993) assumes a range of 0 to -23°C in it's description of precipitation from mixed phase clouds (using the expanded microphysical description of Sundqvist (1988) which includes a representation of the Bergeron-Findeison processes). Observations presented by Matveev (1984) of the frequency of occurrence of ice

within clouds suggest significant amounts of water at temperatures below -20°C. This data was used by Rockel et al (1991) to provide a description of mixed phase clouds in a study of their radiative properties and is now used in the ECHAM model for the purposes of calculating precipitation rates from mixed phase clouds (Lohmann, personal communication). The study of Bower et al (1995) (an extension of the earlier work of Moss and Johnson, 1994) provides an analysis of both layer-cloud and convective cloud in regard to the presence of ice in clouds. They find substantial amounts of liquid water in convective clouds at temperatures as low as -40°C. This may imply that earlier studies contained a significant contribution from convective clouds. They suggest the difference in behaviour is due to the impact of the stronger vertical velocities in convective clouds upon the efficiency of the Hallett-Mossop ice production mechanism. This ice splintering mechanism, first suggested by Hallett and Mossop (1974) operates within the temperature range -3 to -8°C. Fast upward moving air within convective clouds will spend less time within this temperature regime and so ice amounts will be reduced compared to layer clouds with lower vertical velocities.

The sensitivity of the radiation budget of the Unified Model to a wider mixed phase cloud temperature regime (0 to -30°C) is illustrated in figure 10. This shows zonal mean albedo (for a single JJA) from a further integration in which a linear increase in the fraction of cloud treated as water is assumed with increasing temperature, from zero at -30°C to unity at 0°C. Through most of this range this is a close fit to the parametrization of Rockel et al (1991) noted above. Increasing the range of the mixed phase temperature regime implies that more condensate within clouds is treated as water and hence is precipitated less efficiently, leading

to an increase in cloud amount and albedo, worsening agreement with ERBE observations. Also the use of f_L to estimate the effective radius of particles in mixed phase clouds results (with the values of effective radius specified here) in a lower value and so a larger single scattering albedo.

Figure 10 also shows albedo from an experiment in which the mixed phase cloud parametrization is removed, i.e. all cloud water above the freezing level is treated as ice for the purposes of precipitation and estimation of cloud optical properties. Albedos are much reduced in the northern hemisphere (during summer), bringing the simulated value closer to ERBE estimates. This is associated with larger reductions in cloud cover and cloud water content compared to those described when the MRF parametrization is introduced; upto 18% and 40×10^{-3} g/kg respectively in zonal mean values during JJA at 80N, compared with 8% and 20×10^{-3} g/kg with the MRF parametrization. Again the impact of f_L upon the effective radius of mixed phase clouds will also act to reduce cloud albedos in this case.

These results suggest that a narrow temperature range is to be preferred for the representation of mixed phase clouds. Indeed reconsideration of figure 3 shows high ice contents in some clouds at temperatures well above -9°C. However, although the introduction of a parametrization with a smaller temperature range than the 0 to -9°C considered here might seem advantageous to improved model performance, it must be recognised that other deficiencies in the precipitation scheme, and also the great uncertainty in the specification of ice optical properties may also contribute to model errors.

Although uncertainties exist in the parametrization of mixed phase cloud, the above results show the importance of such clouds to accurate simulation of the present day climate. Such representations need to be further improved if greater confidence in climate simulations is to be obtained. More detailed parametrizations of cloud microphysics are being developed for the next generation of climate models. Ballard and Hutchinson (1995) present preliminary results from a frontal simulation using the mesoscale version of the Unified Model (with a horizontal resolution of 16km) using a cloud scheme with detailed (bulk) microphysics. A wide spread of ice water contents between 0 and -6°C was simulated as suggested by figure 3.

One of the motivations for this study stated in the introduction was to reduce the uncertainty in the predictions of climate change experiments due to the differing natures of the cloud-radiation feedback in different models or when different parametrizations are used. A measure of climate sensitivity to changes in climate forcing (caused by variations of boundary conditions through increased levels of greenhouse gases or modified sea surface temperatures is the "sensitivity parameter" (λ) defined by Cess and Potter (1988) to be,

$$\lambda = - \frac{\Delta T_s}{\Delta R} \qquad (5)$$

where ΔT_s is the surface temperature change and ΔR the corresponding change in the top of atmosphere radiation budget.

As discussed in the introduction, Li and Le Treut (1993) report a large change in the value

of λ from 0.96K/Wm^{-2} to 0.62K/Wm^{-2} when the temperature below which cloud condensate is treated as ice is changed from -15°C to 0°C, estimated from the response of the LMD GCM to a ±2K change in sea surface temperature. For a similar experiment the version of the Hadley Centre climate model (at 2.5x3.75° lat.-long. resolution) has a λ of 0.66K/Wm^{-2} (Ingram, personal communication). This result is obtained with the standard mixed phase cloud parametrization (with a temperature range of 0 to -15°C) and is closer to the value from the LMD model assuming cloud condensate is ice below 0°C.

The aim of such simple "climate change" experiments is to provide an estimate of GCM sensitivity to changes in radiative forcing (Cess et al 1988). However Senior and Mitchell (1993) showed that there was little agreement between the sensitivity parameter estimated from ±2K SST simulations and those for a doubling of the atmospheric concentration of CO_2. Preliminary analysis of experiments using the same version of the Hadley Centre climate model as used in the ±2K SST experiments reported above but coupled to a thermodynamic (slab) ocean model show that at equilibrium on an instantaneous doubling of the amount of CO_2 in the atmosphere the sensitivity parameter changes only by a small amount when the standard mixed phase parametrization is replaced by the MRF version, from 0.88 to 0.8K/Wm^{-2} (Senior and Carnell personal communication). This change is of smaller magnitude but is in the same sense as that reported by Li and Le Treut (1993) for a related change in the treatment of ice precipitation (although their experimental design is rather different). Indeed a smaller magnitude might be expected as the change in temperature range between the standard and MRF parametrization (3K on average) is smaller than the change

used by Li and Le Treut (15K) and, as demonstrated above, results in smaller changes to the cloud fields than removing the mixed phase parametrization altogether. However it is interesting to note that the ratio between the change in sensitivity parameter found by Li and Le Treut (0.34) to that due to the change from the standard to the MRF parametrization (0.08) is approximately five, the same ratio as the average temperature change in the mixed phase regime between these studies, perhaps suggesting that the changes in climate sensitivity of these two models to the temperature range over which mixed phase clouds are assumed to exist are comparable.

Further comments regarding whether the introduction of the observationally based treatment of mixed phase cloud does reduce the uncertainty in climate change experiments will have to await more parallel experiments between different models. However the improved simulation of present day climate with the introduction of the revised scheme does give more confidence in the ability of the model to simulate climate accurately, a prerequisite for gaining confidence in the ability of GCMs to provide accurate estimates of future climates.

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LIST OF FIGURES

Figure 1 : Comparison of zonal mean albedo from a 2.5x3.75° (short dash) (3 year mean) and 5x7.5° lat-long (long dash) (4 year mean) version of the Unified Model against ERBE data (averaged between 1987 and 1991) (solid) for June/July/August (4 year means).

Figure 2 : Plot of the proportion of liquid water to total condensate in cloud against ambient temperature (fig 7 from Moss and Johnson, 1994). The aircraft data are shown as crosses, the standard mixed phase parametrization (Smith, 1990) as a solid line and the linear best fit to the aircraft data as a dashed line.

Figure 3 : Precipitation rate as a function of cloud water content for the microphysical formulation used in the Unified Model for a 1000m thick cloud assuming an air density of unity. Ice (solid), rain (oceanic cloud) (dash triple dot) and rain (continental cloud) (short dash).

Figure 4 : Albedo estimated from ERBE data (1987-1991) for (a) June/July/August and (b) December/January/February.

Figure 5 : Difference of model simulated albedo (4 year means) from ERBE observations for integrations using the standard mixed phase cloud parametrization (a) June/July/August, (b)

December/January/February and MRF mixed phase cloud parametrization (c) June/July/August, (d) December/January/February. A contour interval of 0.1 is used, with dashed lines indicating negative values. Values greater than zero are shaded, with medium shading above 0.1 and dark shading above 0.2

Figure 6 : Comparison of zonal mean albedo and top of atmosphere outgoing long wave radiation (4 year means) against ERBE data. Albedo : (a) June/July/August, (b) December/January/February. OLR : (c) June/July/August, (d) December/January/February. Standard mixed phase cloud parametrization (long dash), MRF mixed phase cloud parametrization (short dash), ERBE (solid)

Figure 7 : Zonal mean cloud amount for integration with standard mixed phase cloud parametrization, (a) June/July/August and (b) December/January/February (4 year means) and difference in cloud amount which results from the introduction of the MRF mixed phase cloud parametrization, (c) June/July/August and (d) December/January/February (4 year means). For (a) and (b) a contour interval of 0.1 has been used, with values above 0.3 being shaded. For (c) and (d) the contour interval is 0.02, with negative differences shaded. Bold dashed lines show isopleths of 0, -9 and -15°C (from the control experiment).

Figure 8 : Zonal mean grid box mean cloud water contents after precipitation for integration with standard mixed phase cloud parametrization, (a) June/July/August and (b) December/January/February (4 year means) and for that with the MRF mixed phase cloud

parametrization, (c) June/July/August and (d) December/January/February (4 year means). For (a) and (b) a contour interval of $20x10^{-3}$g/kg is used while for (c) and (d) the contour interval is $5x10^{-3}$g/kg, with negative values shaded. Bold dashed lines show isopleths of 0, -9 and -15°C (from the control experiment) are plotted on each chart.

Figure 9 : Comparison of zonal mean albedo (single seasons) against ERBE data for (a) June/July/August, (b) December/January/February. Standard mixed phase cloud scheme (long dash), MRF mixed phase cloud parametrization (short dash) and ERBE (solid).

Figure 10 : Comparison of zonal mean albedo against ERBE data for June/July/August (single season). Standard mixed phase cloud parametrization (long dash) , MRF mixed phase cloud parametrization (short dash), 0 to -30°C mixed phase cloud parametrization (dash triple dot),

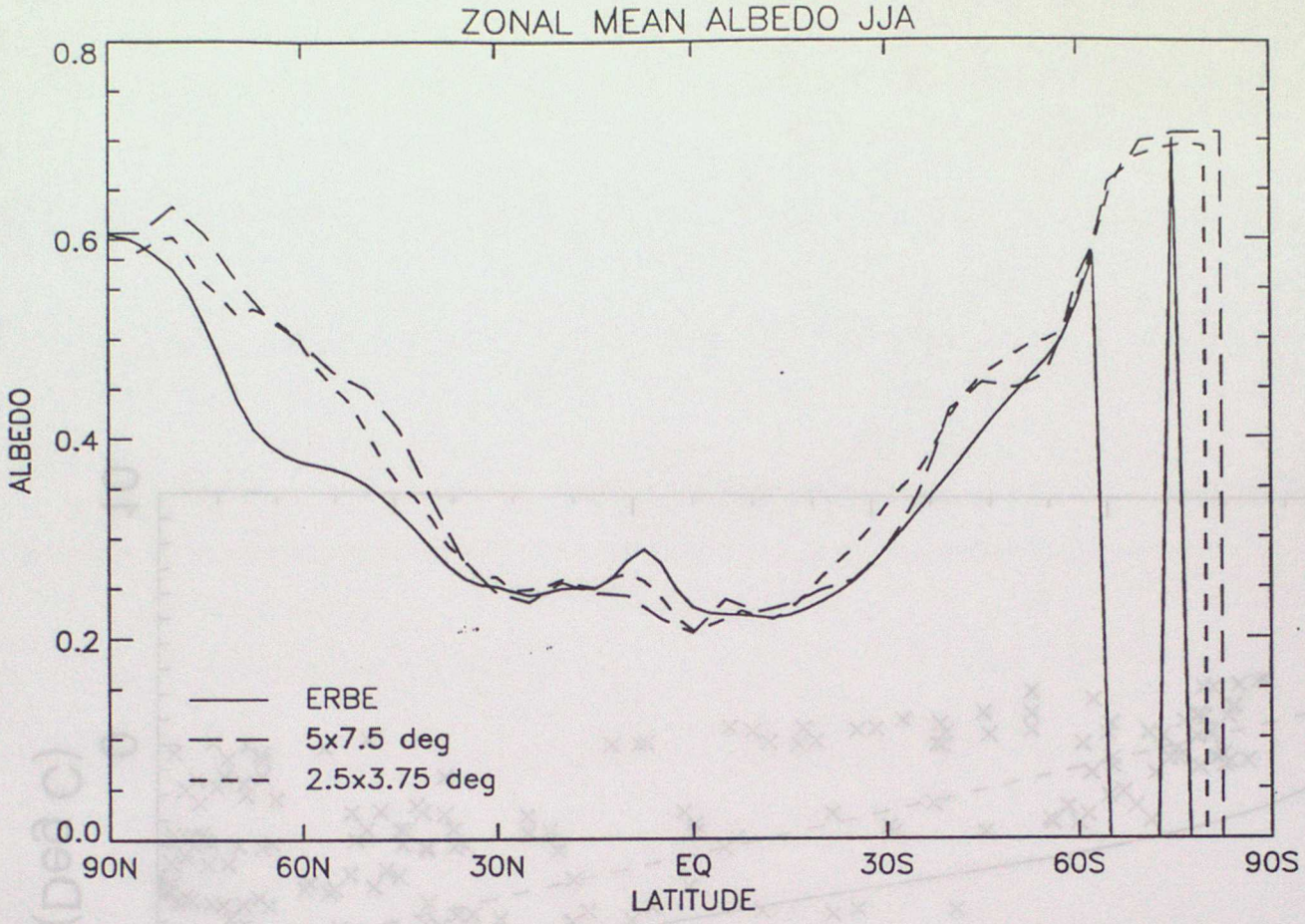

ZONAL MEAN ALBEDO JJA
0.8
0.6
0.4
0.2
0.0
ALBEDO
ERBE
5x7.5 deg
2.5x3.75 deg
90N
60N
30N
EQ
30S
60S
90S
LATITUDE

Figure 1

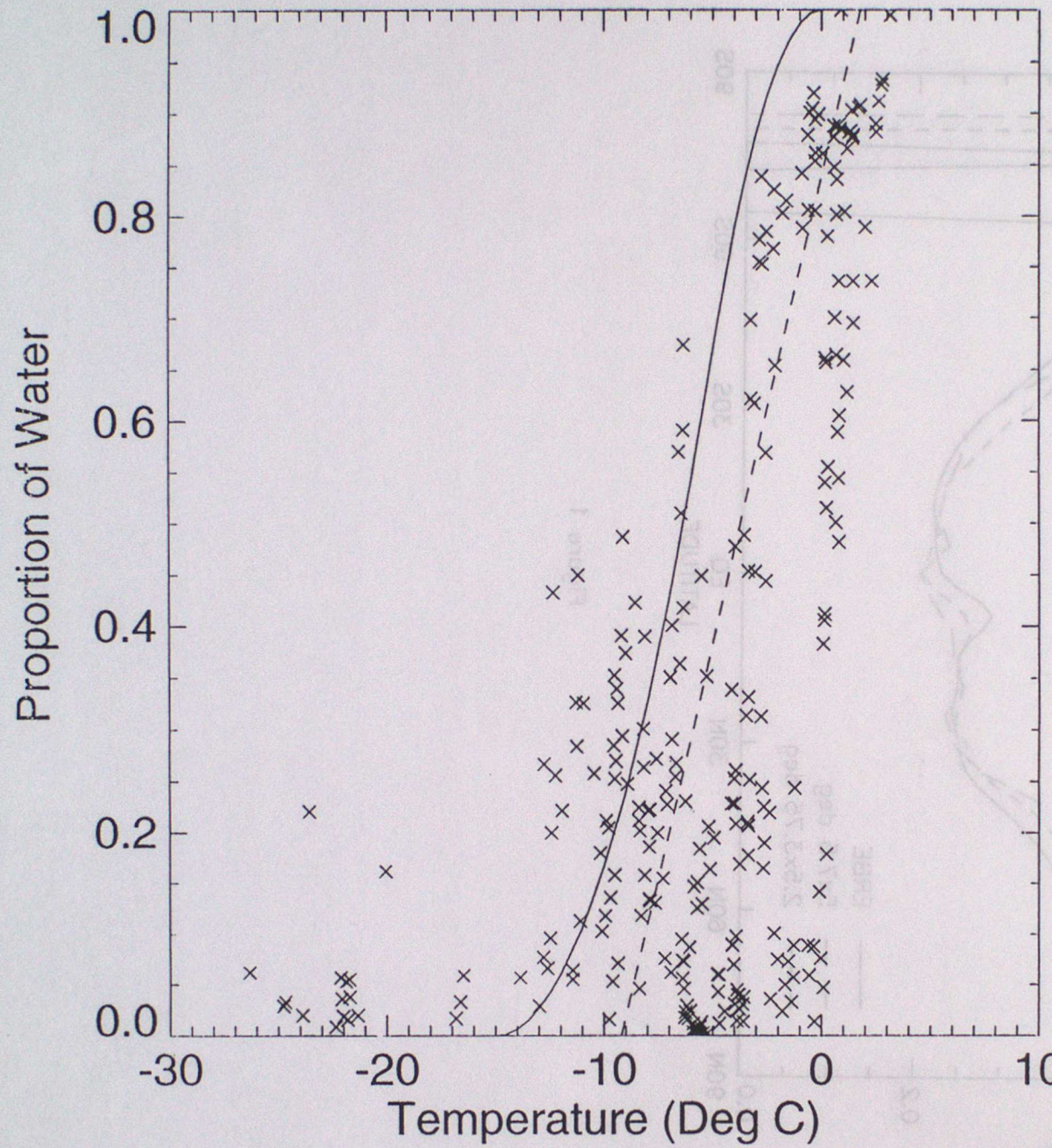

1.0
0.8
0.6
0.4
0.2
0.0
Proportion of Water
-30
-20
-10
0
10
Temperature (Deg C)

Figure 2

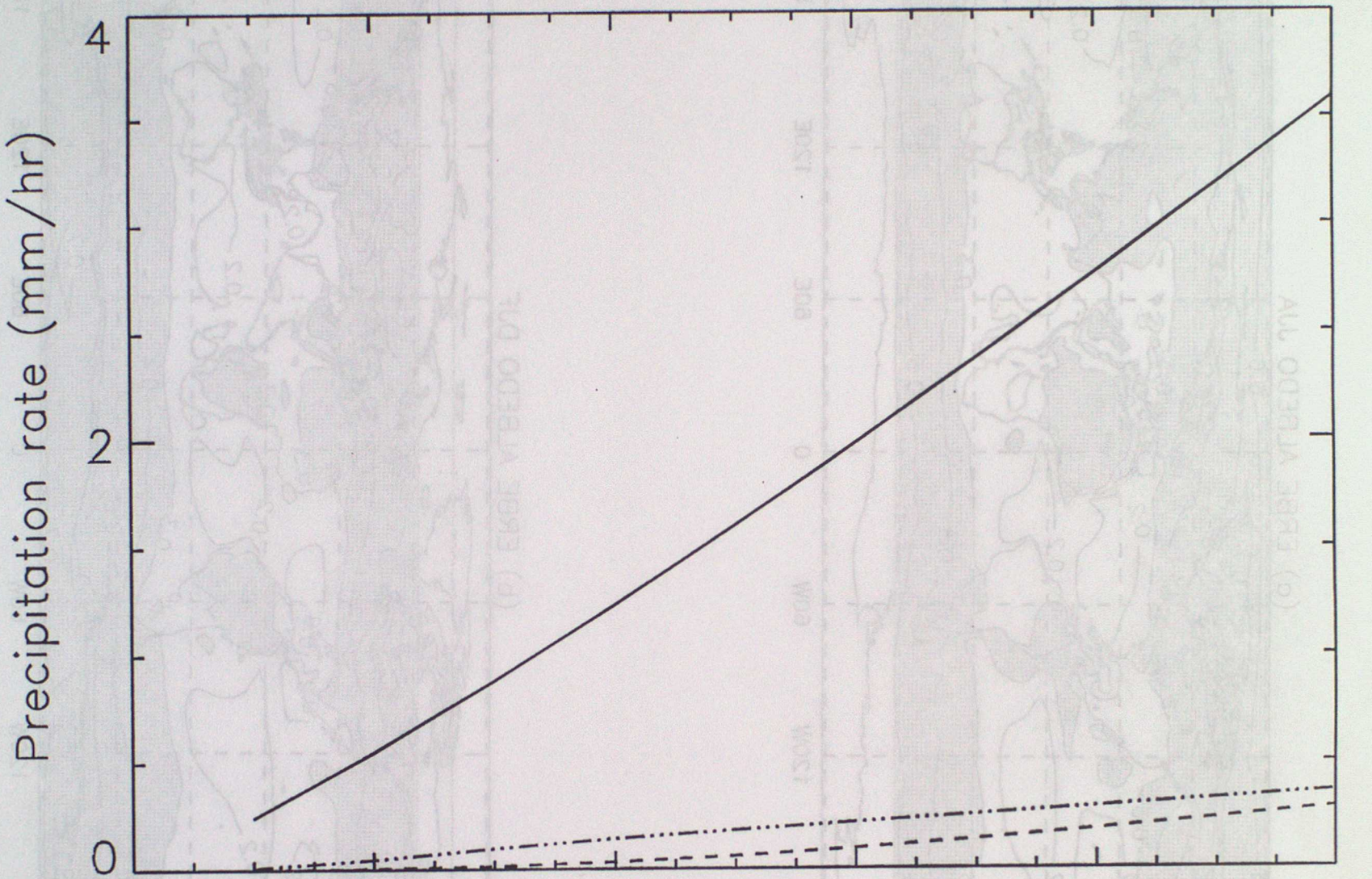
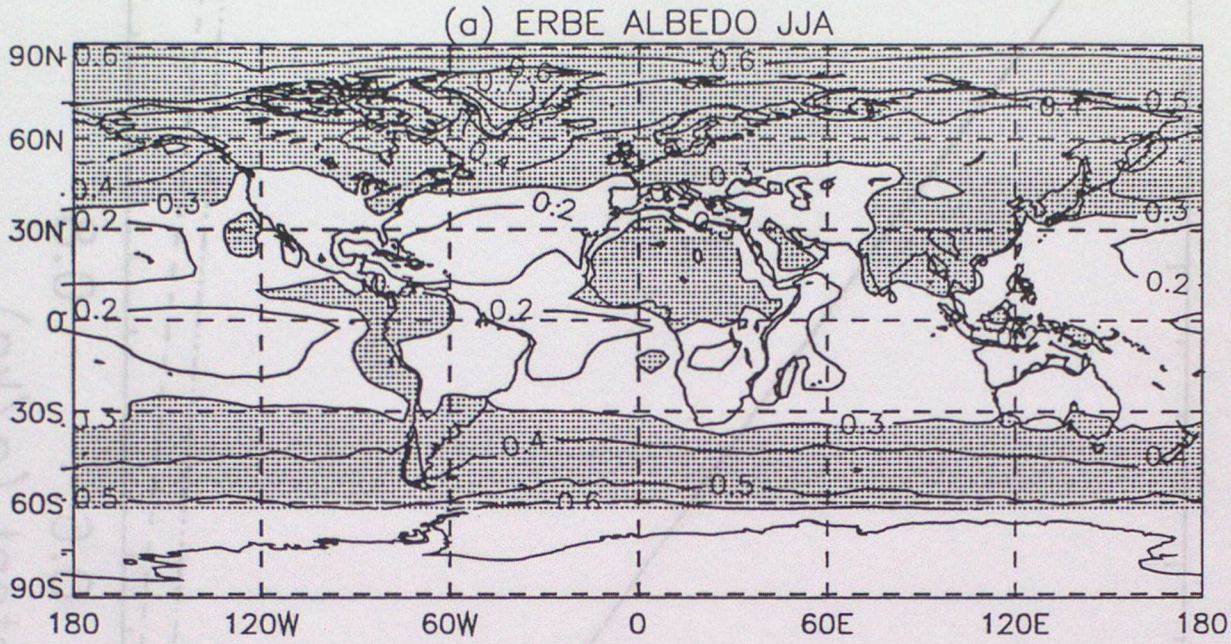

Precipitation rate (mm/hr)
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
Cloud Water Content (g/kg)

Figure 3


(a) ERBE ALBEDO JJA
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180

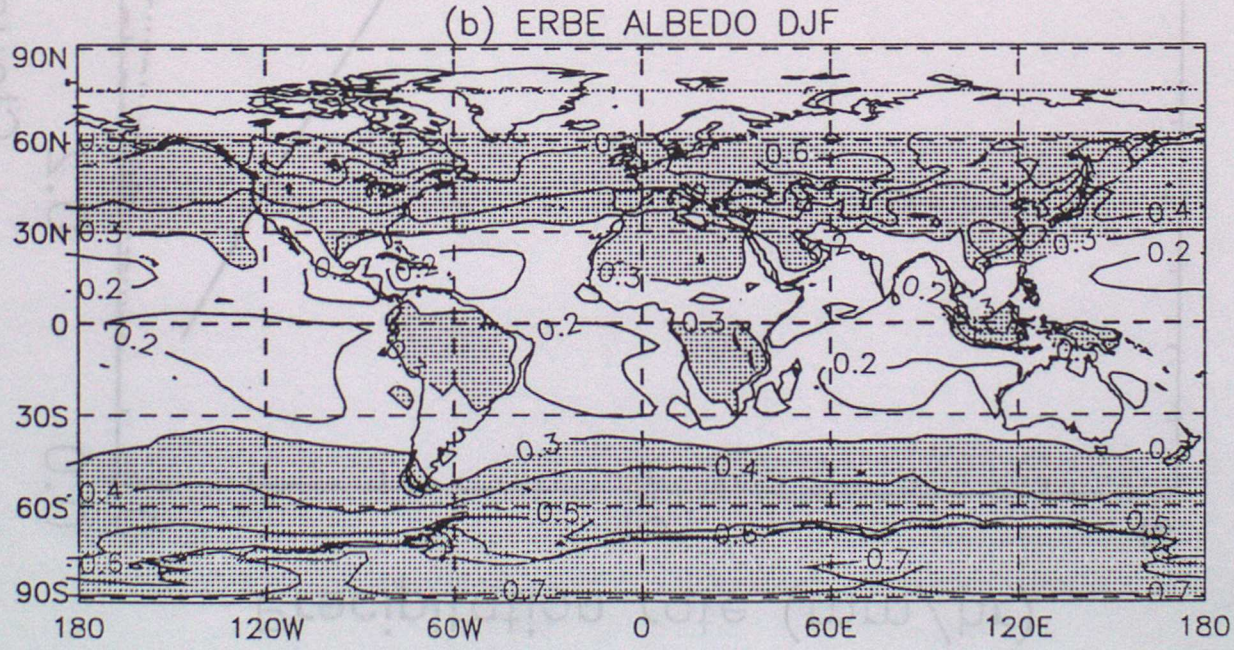
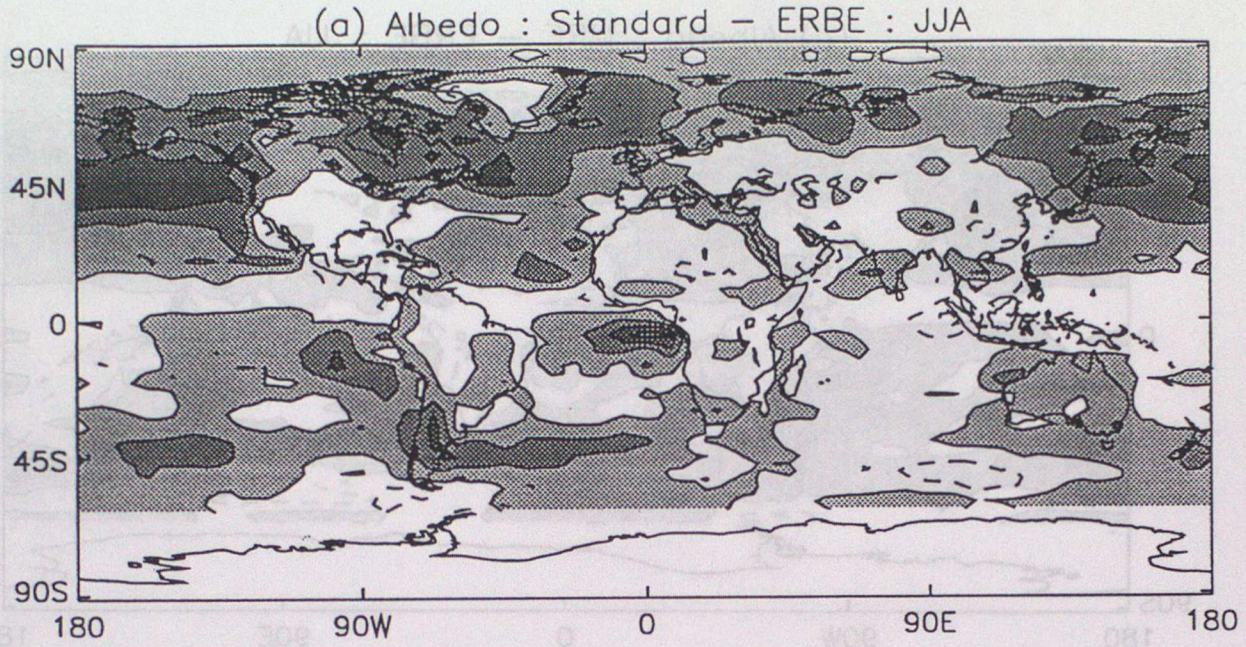

(b) ERBE ALBEDO DJF
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180

Figure 4


(a) Albedo : Standard − ERBE : JJA
90N
45N
0
45S
90S
180
90W
0
90E
180

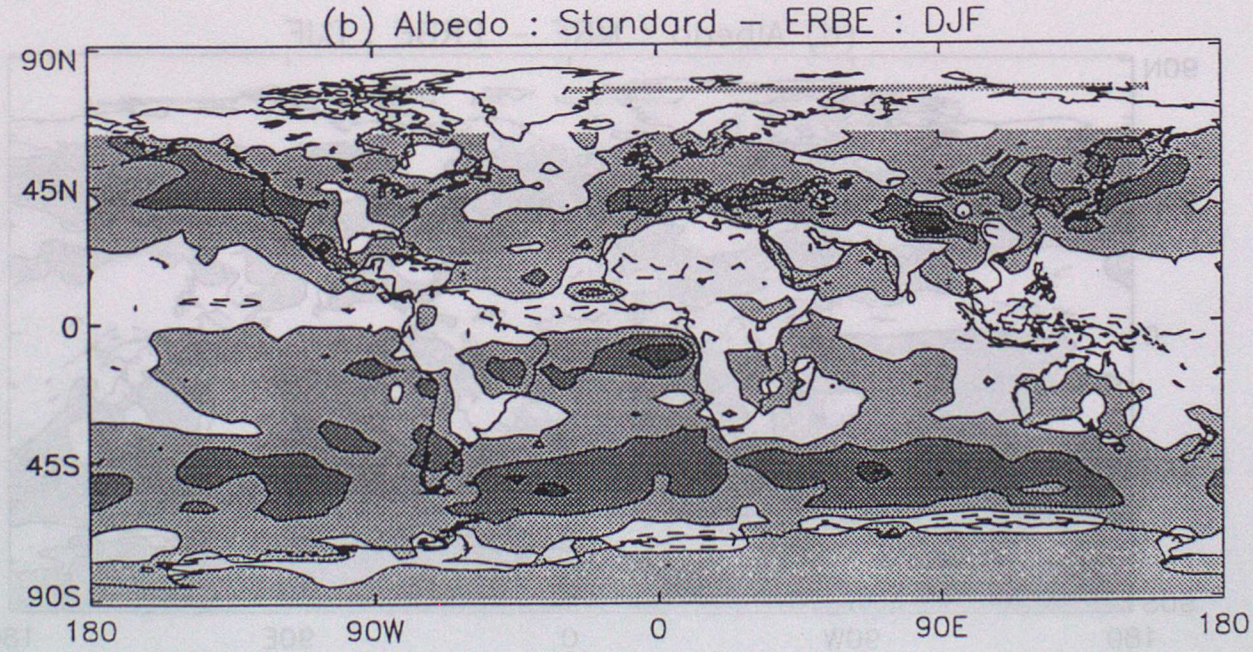
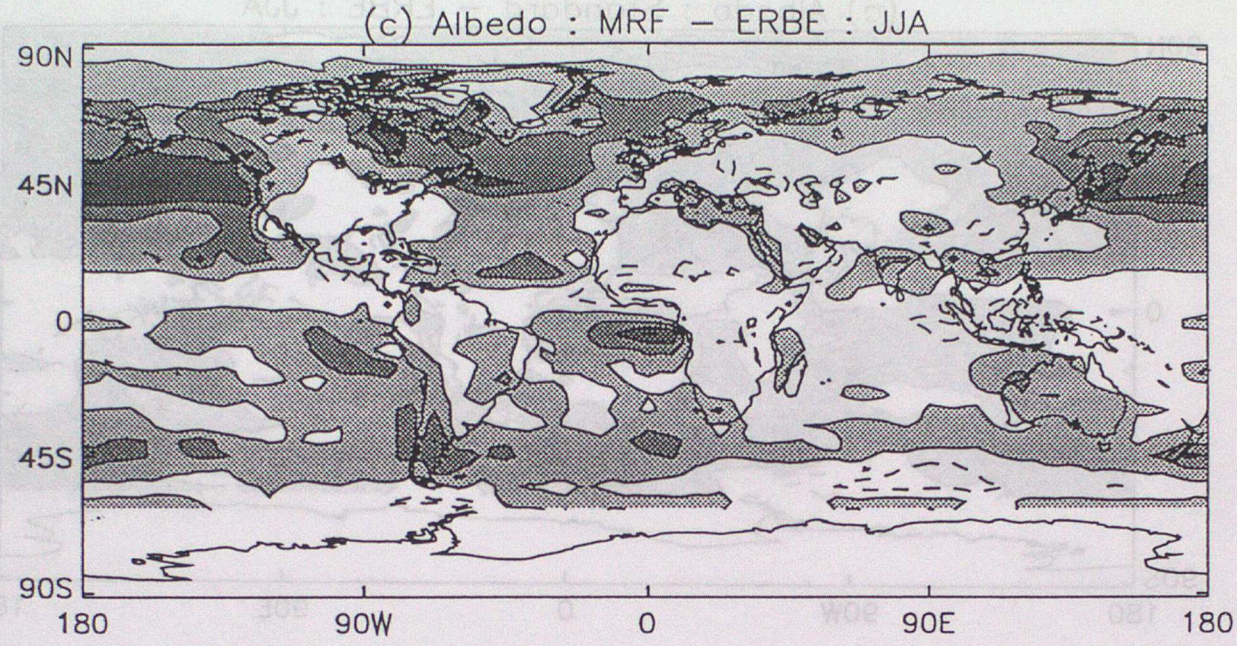
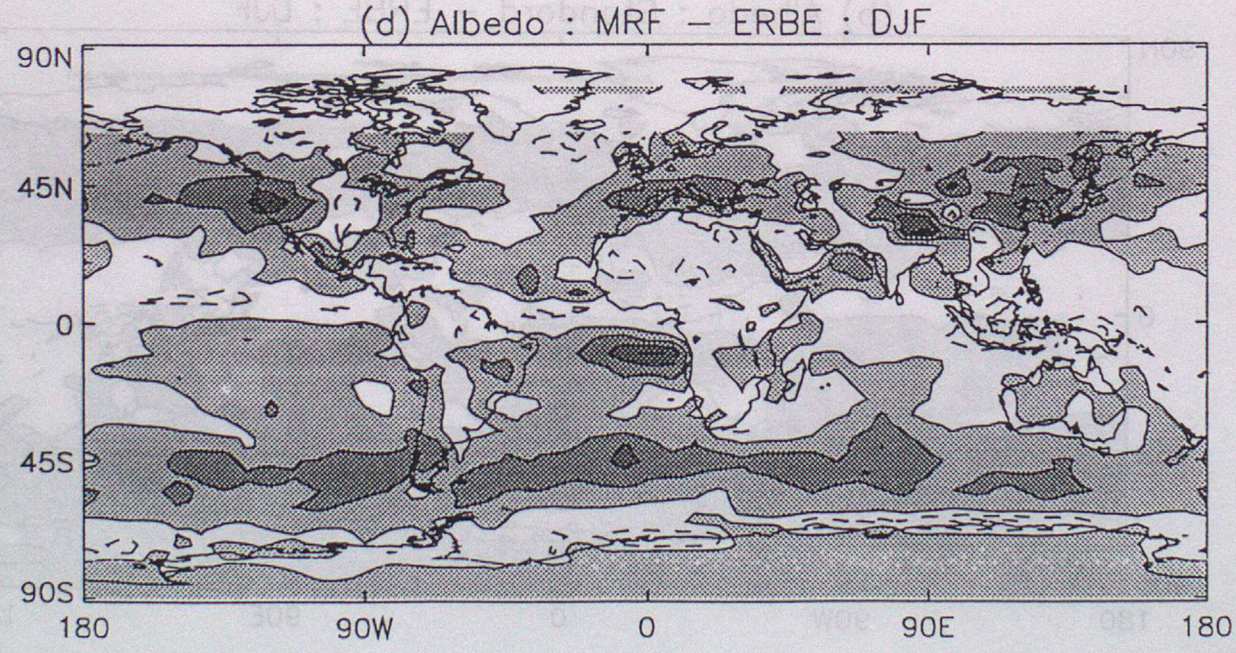

(b) Albedo : Standard − ERBE : DJF
90N
45N
0
45S
90S
180
90W
0
90E
180

Figure 5





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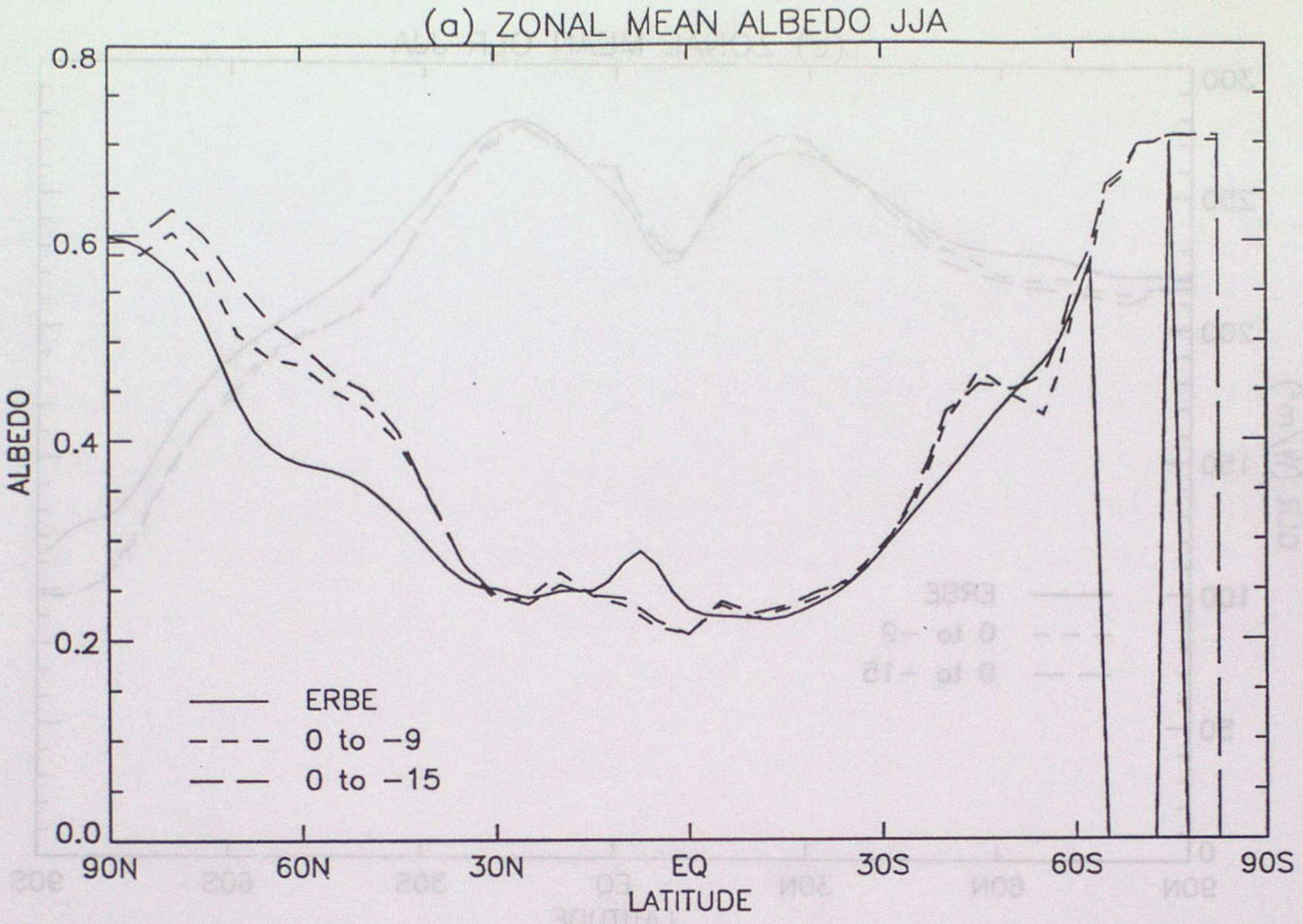

(a) ZONAL MEAN ALBEDO JJA
ALBEDO
0.8
0.6
0.4
0.2
0.0
ERBE
0 to −9
0 to −15
90N
60N
30N
EQ
30S
60S
90S
LATITUDE

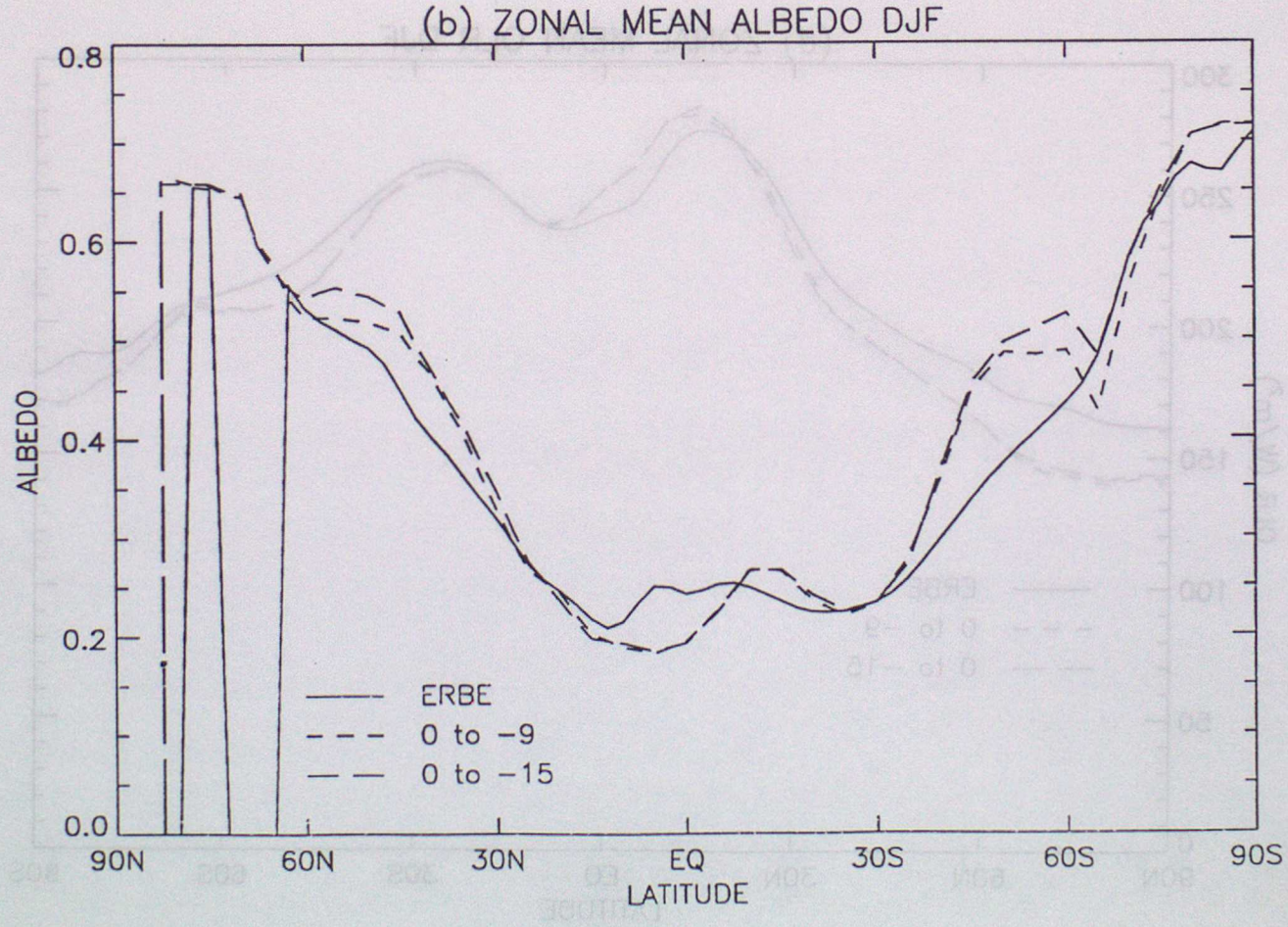
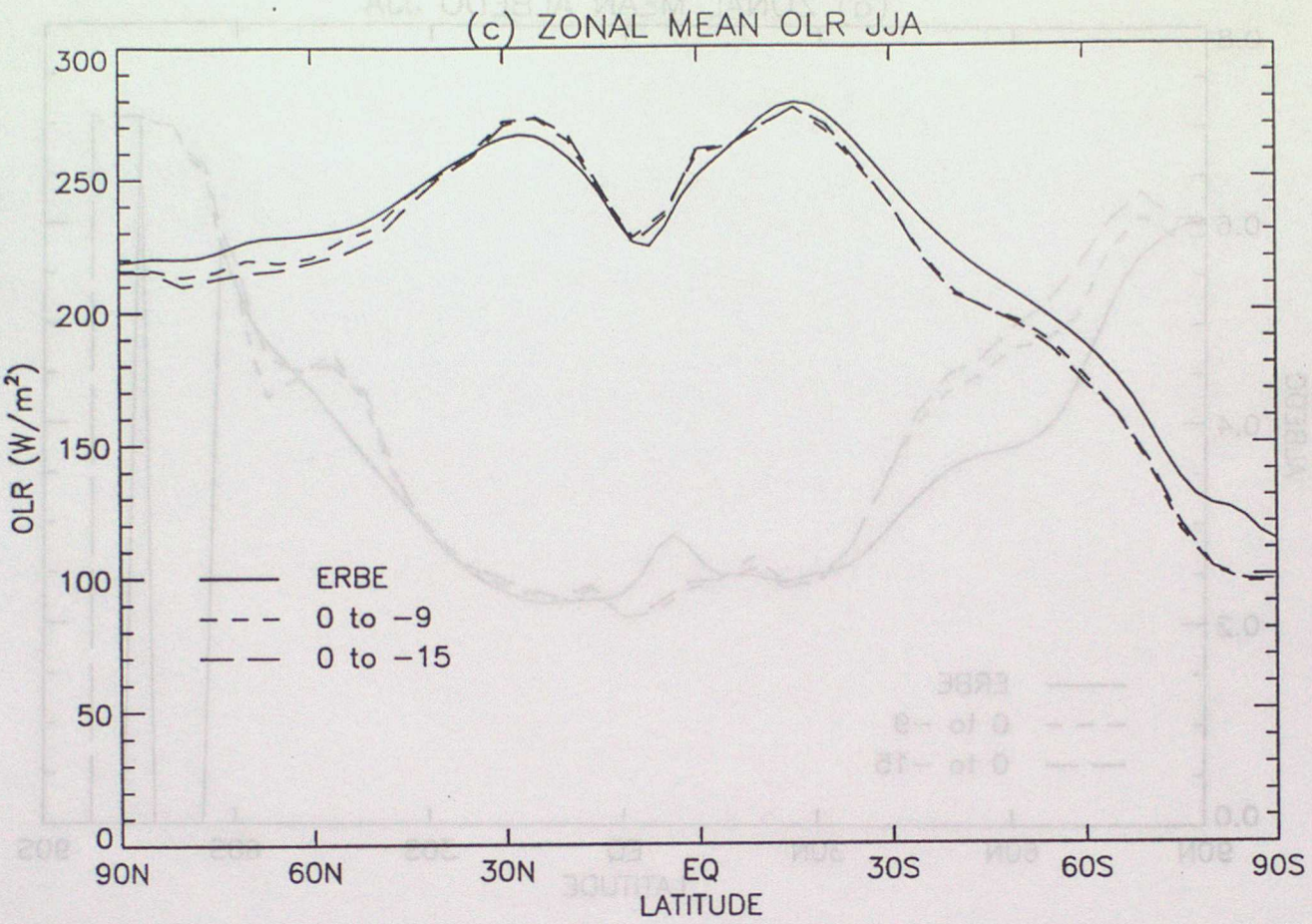

(b) ZONAL MEAN ALBEDO DJF
ALBEDO
0.8
0.6
0.4
0.2
0.0
ERBE
0 to −9
0 to −15
90N
60N
30N
EQ
30S
60S
90S
LATITUDE

Figure 6



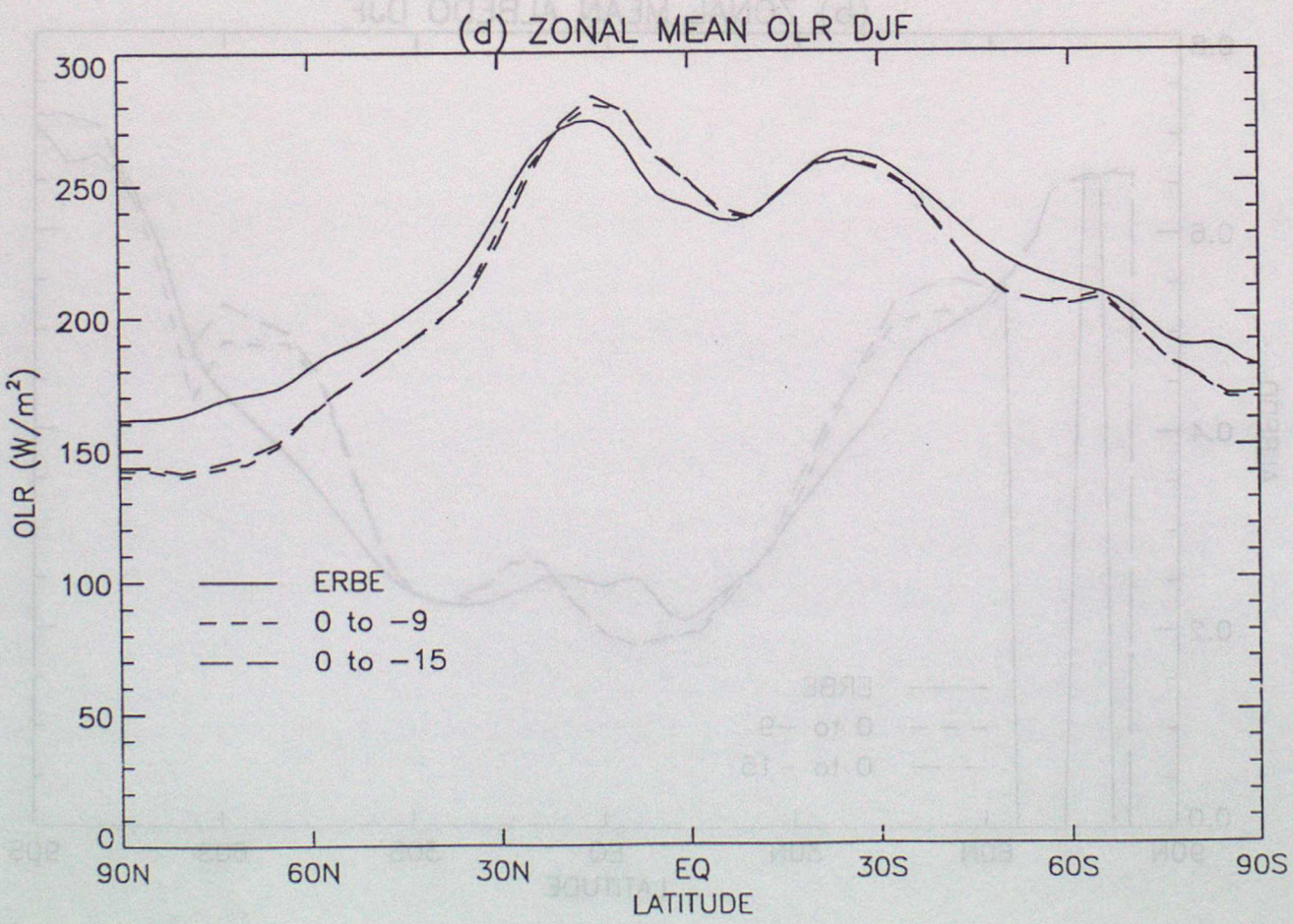
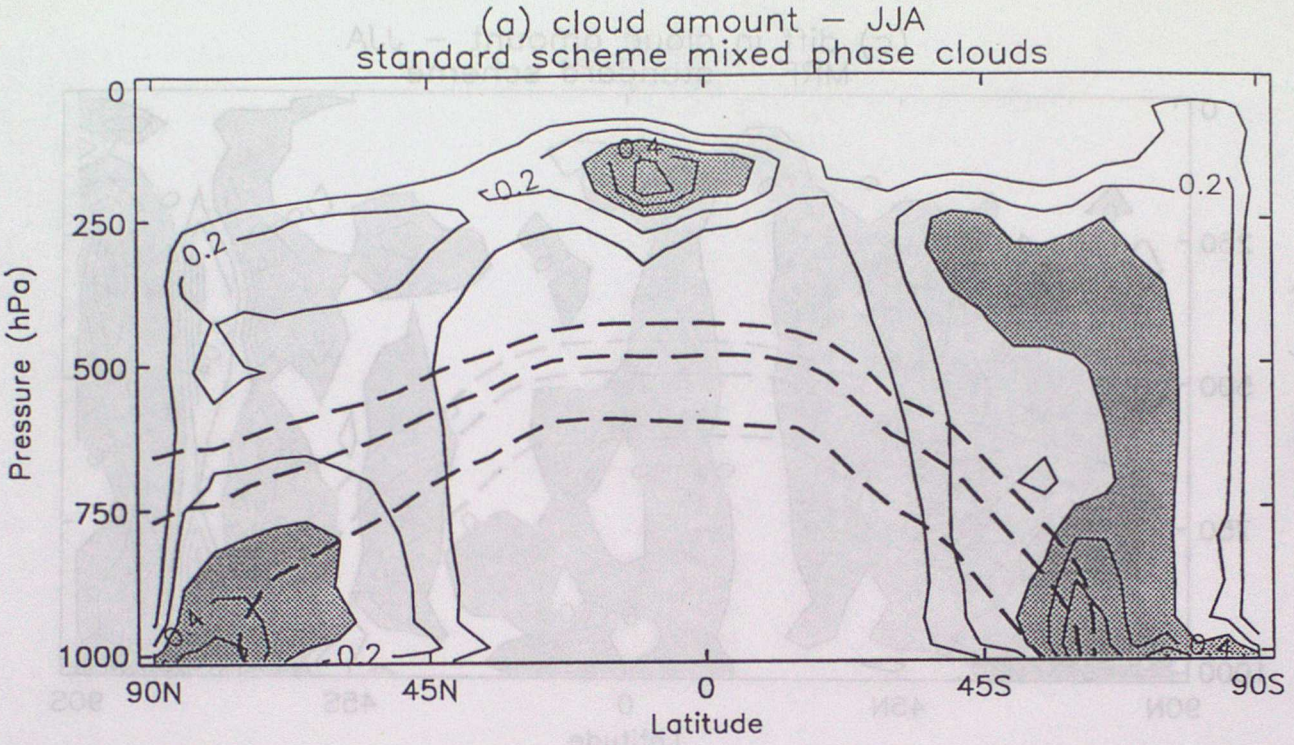


Figure 6 contd


(a) cloud amount – JJA
standard scheme mixed phase clouds
Pressure (hPa)
0
250
500
750
1000
0.2
0.4
90N
45N
0
45S
90S
Latitude

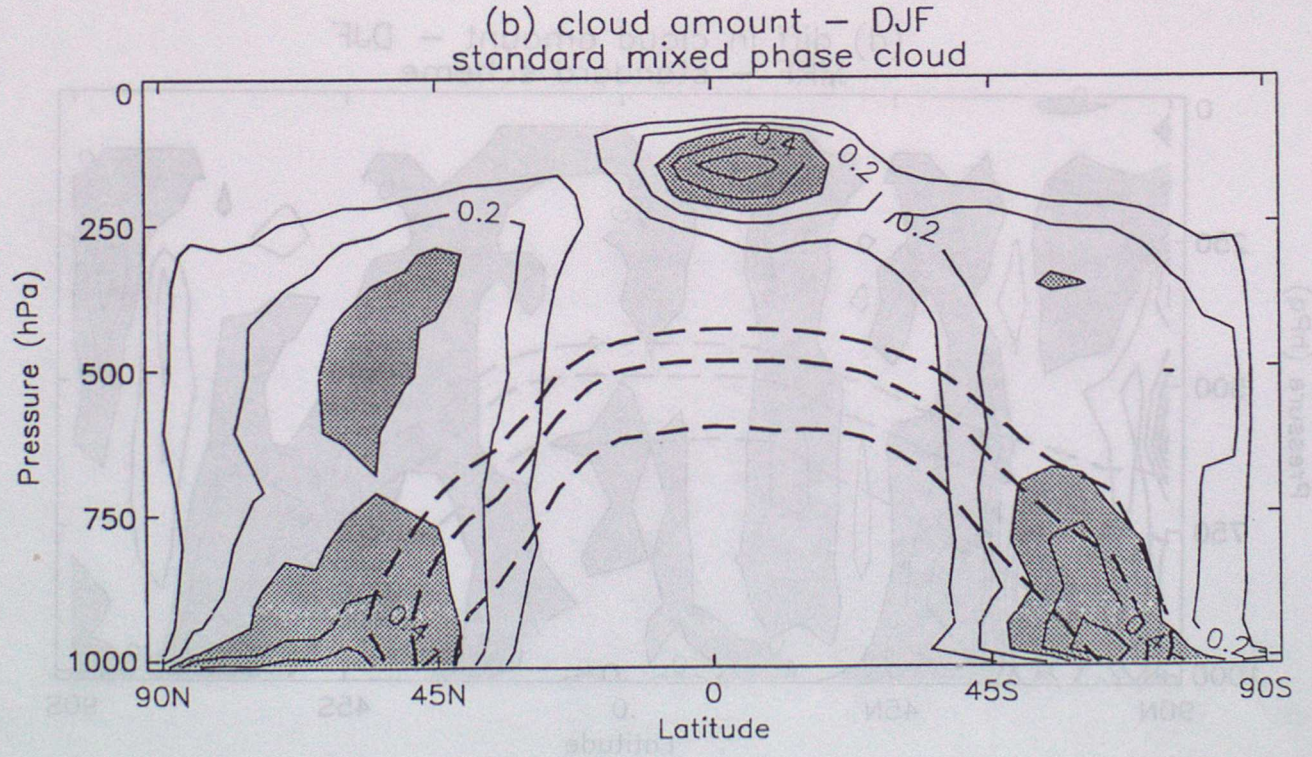
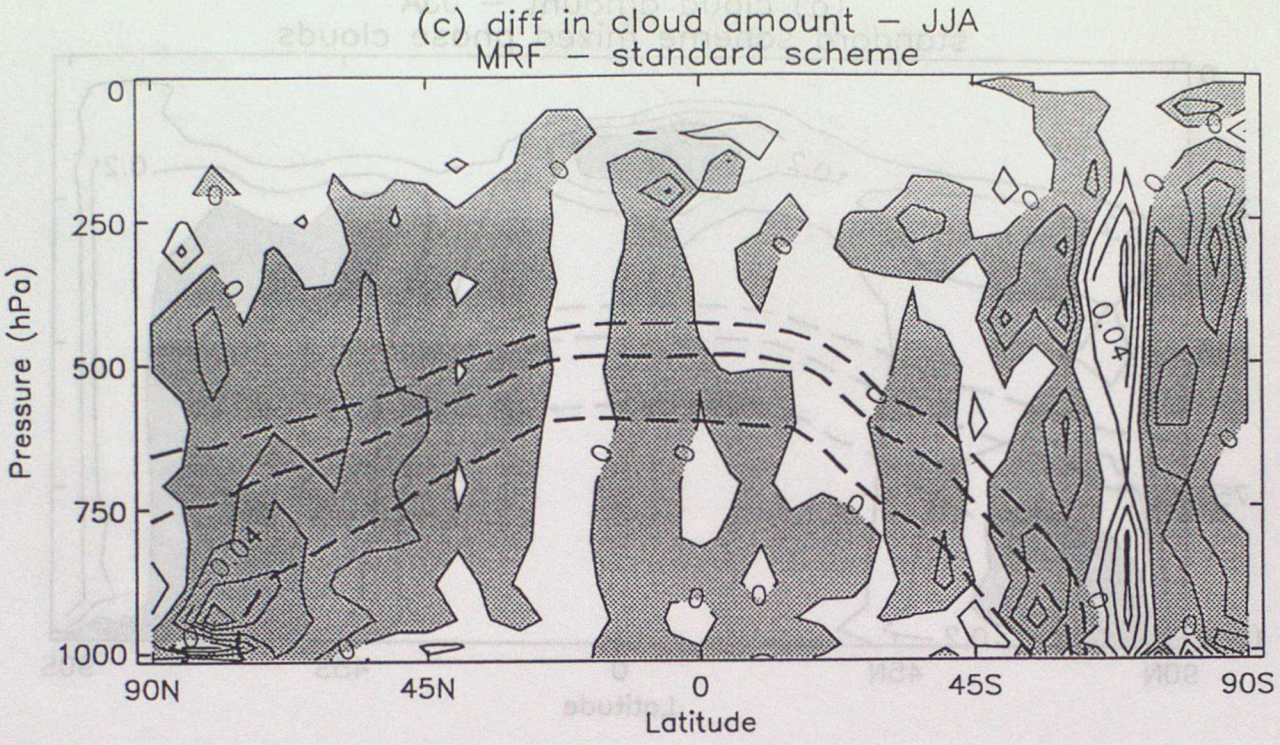

(b) cloud amount – DJF
standard mixed phase cloud
Pressure (hPa)
0
250
500
750
1000
0.2
0.4
90N
45N
0
45S
90S
Latitude

Figure 7



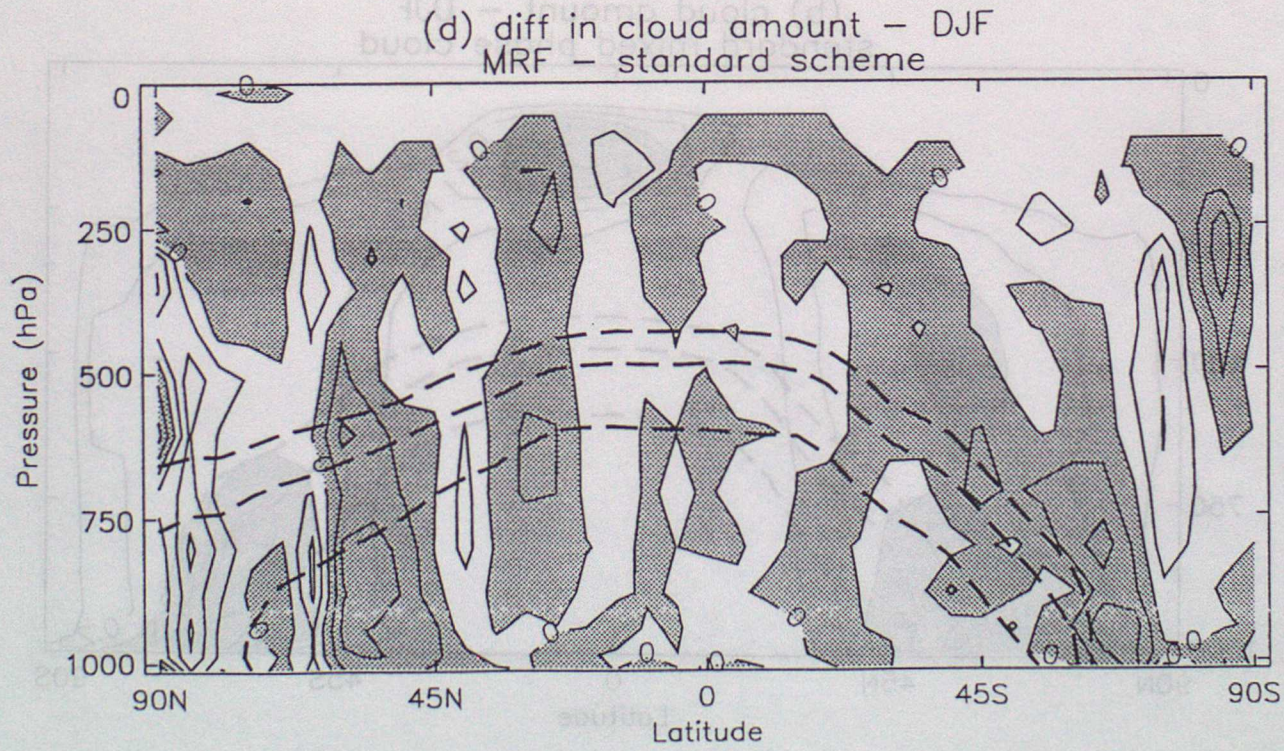
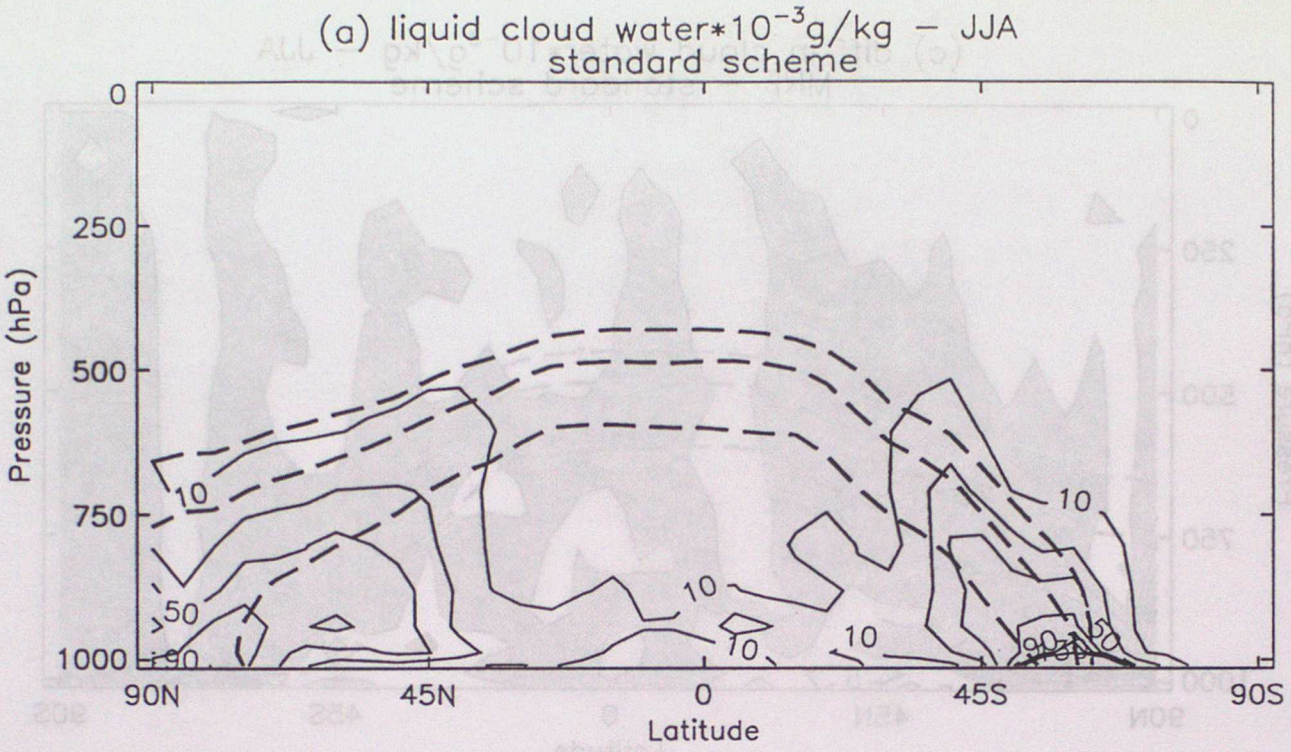


Figure 7 contd


(a) liquid cloud water*10^{-3}g/kg – JJA
standard scheme
Pressure (hPa)
0
250
500
750
1000
90N
45N
0
45S
90S
Latitude
10
50
90

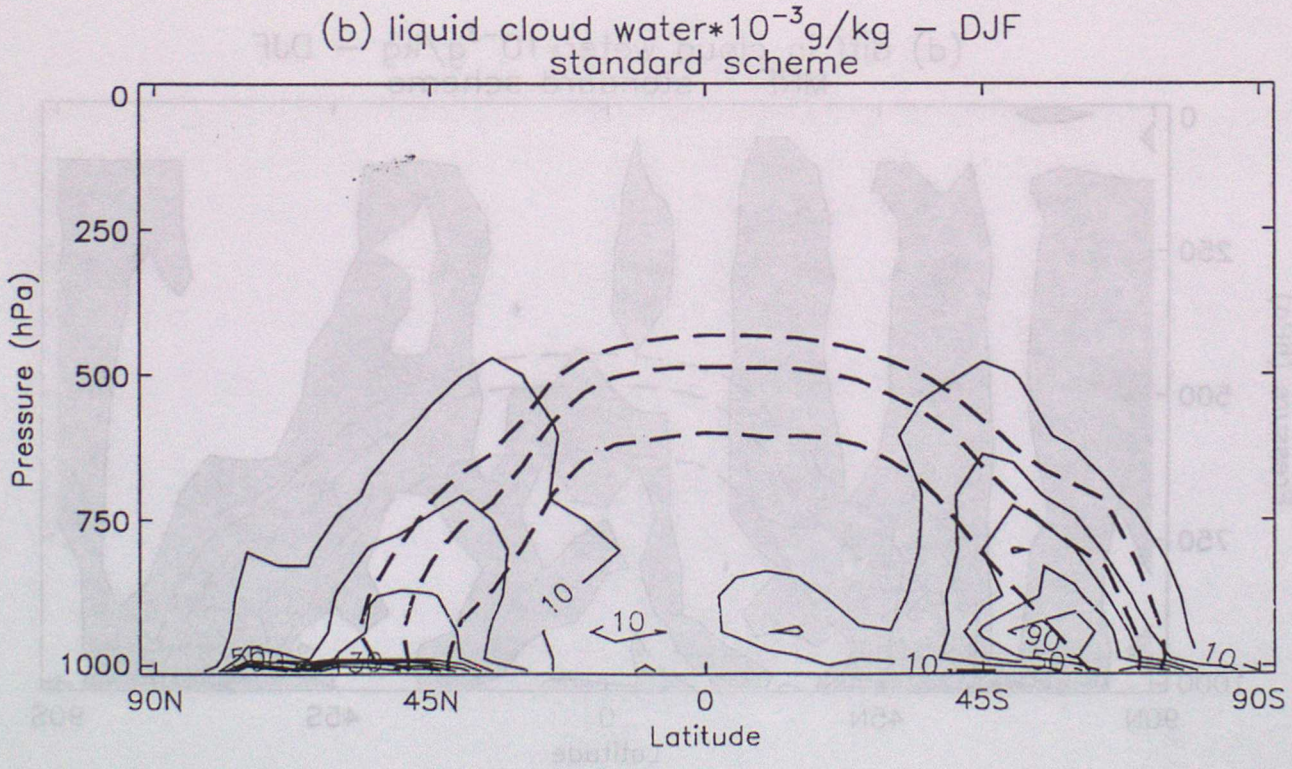
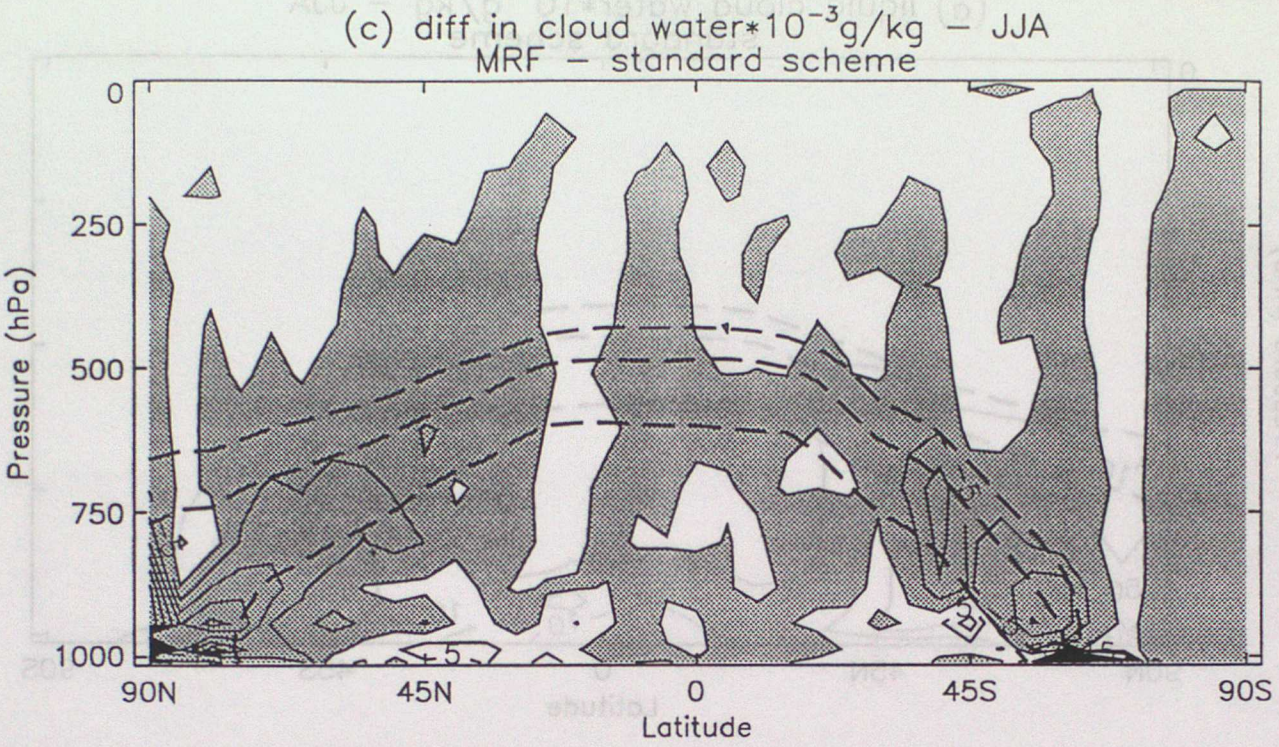

(b) liquid cloud water*10^{-3}g/kg – DJF
standard scheme
Pressure (hPa)
0
250
500
750
1000
90N
45N
0
45S
90S
Latitude
10
50
90

Figure 8



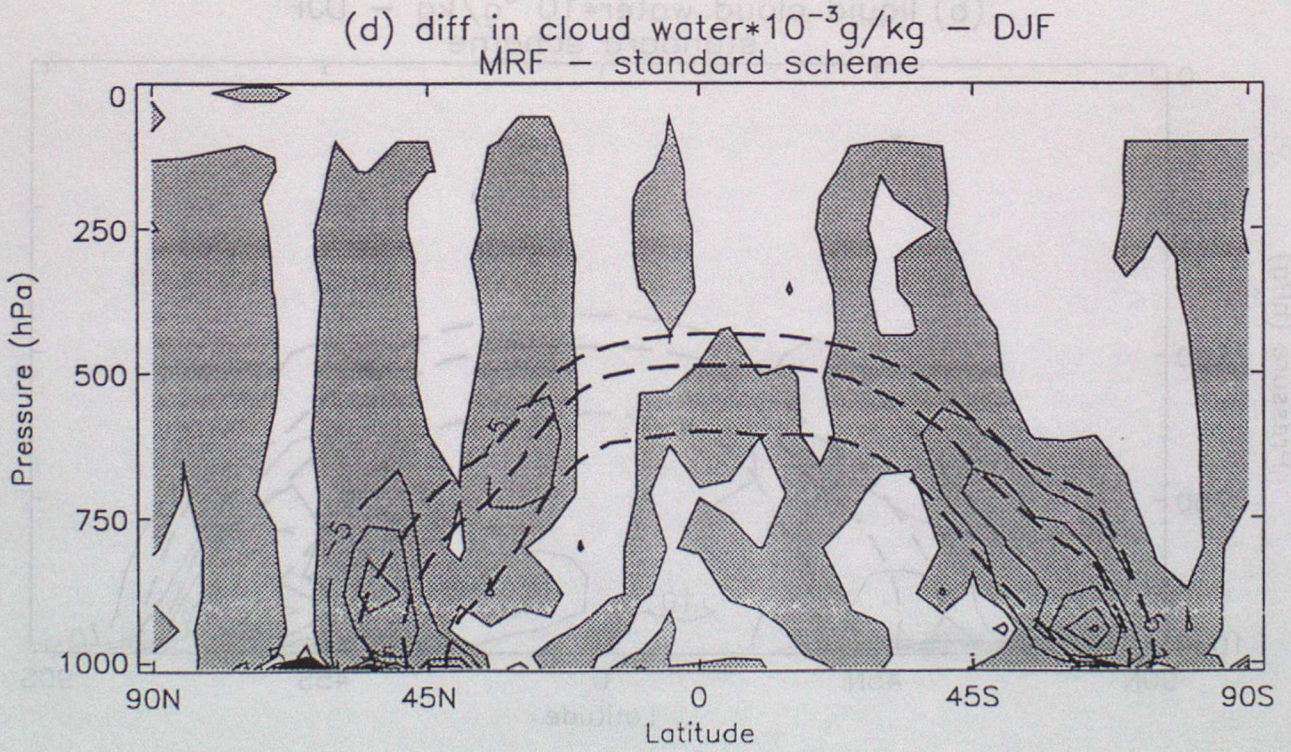
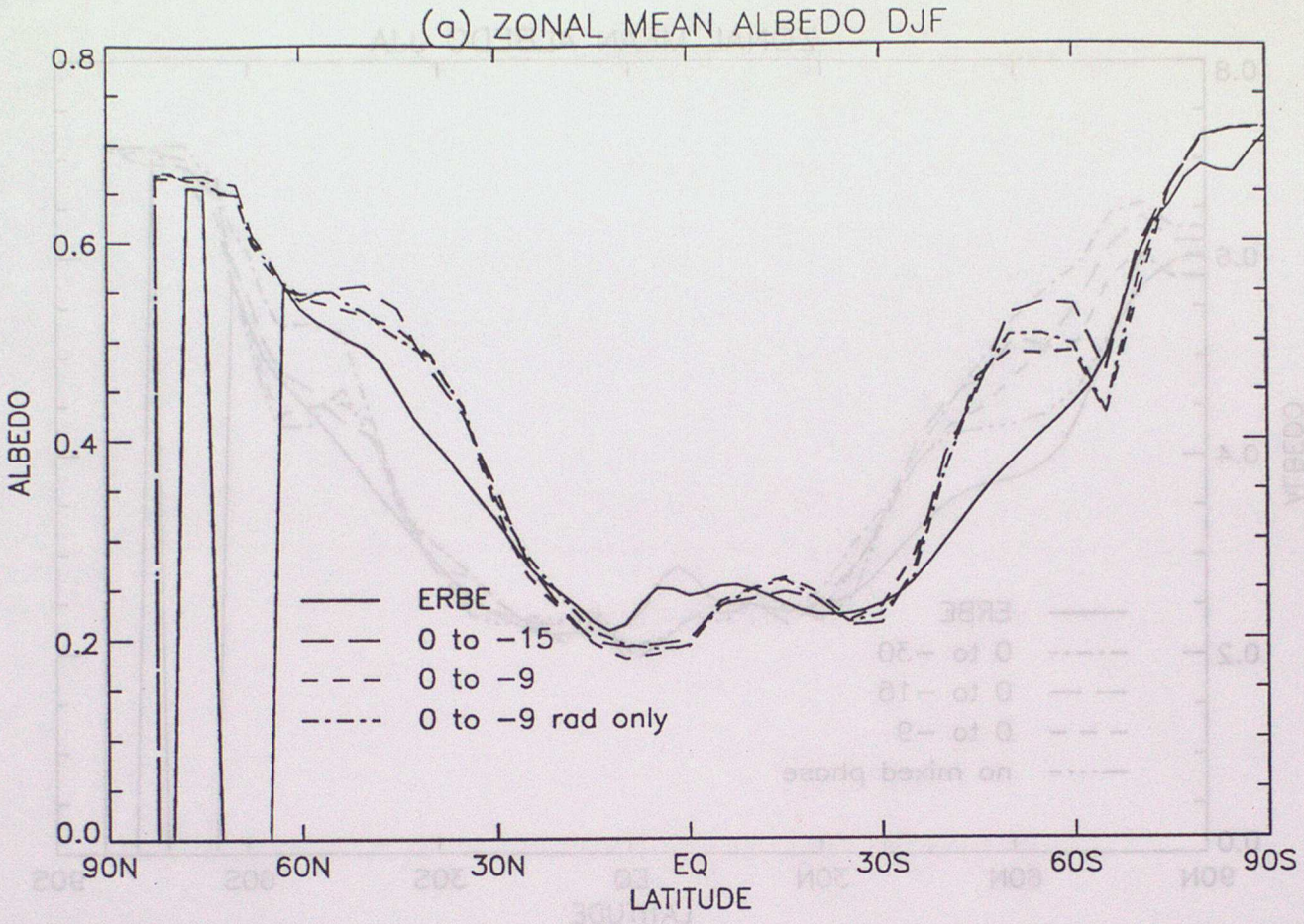


Figure 8 contd


(a) ZONAL MEAN ALBEDO DJF
ALBEDO
0.0
0.2
0.4
0.6
0.8
90N
60N
30N
EQ
30S
60S
90S
LATITUDE
ERBE
0 to −15
0 to −9
0 to −9 rad only

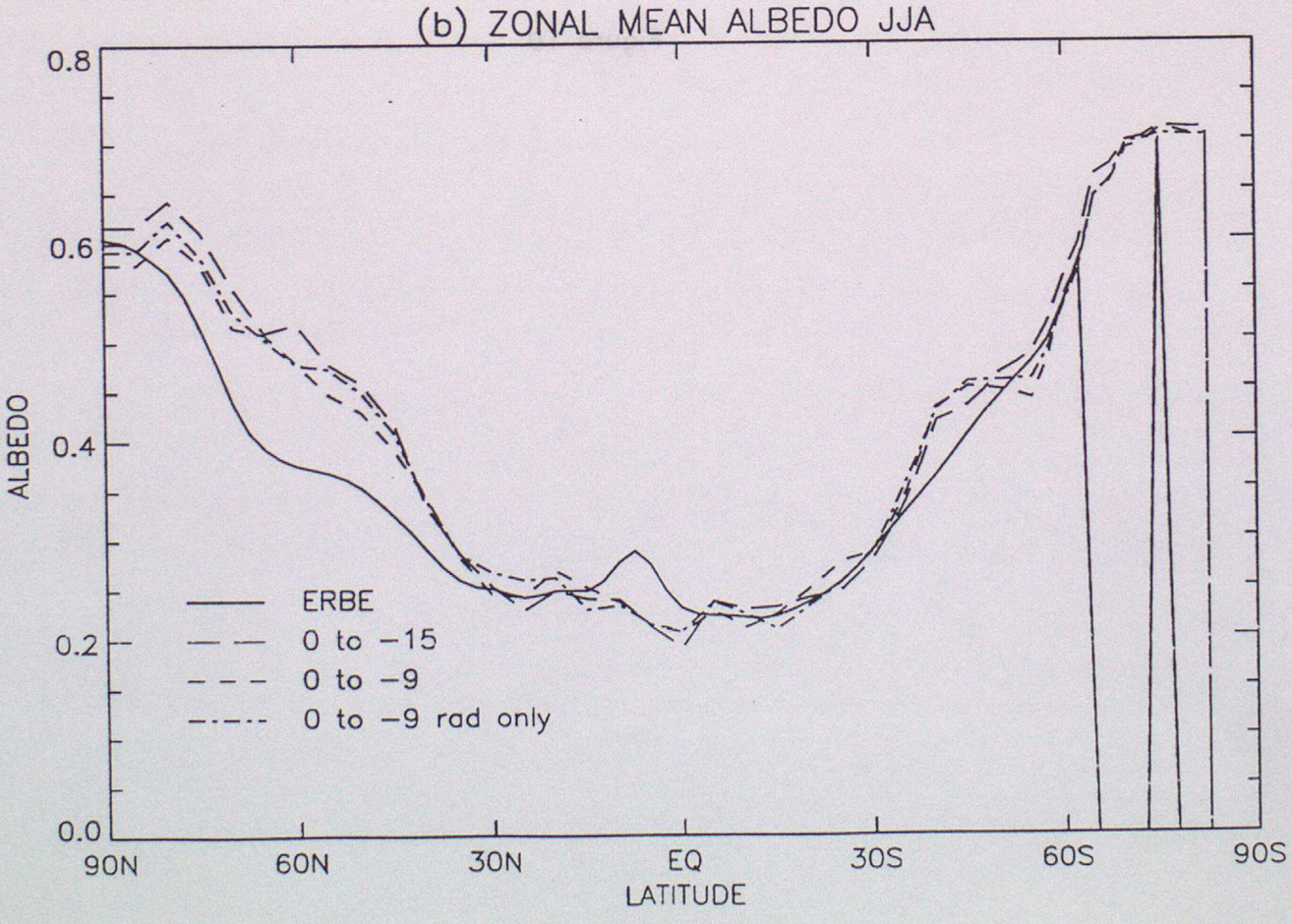

(b) ZONAL MEAN ALBEDO JJA
ALBEDO
0.0
0.2
0.4
0.6
0.8
90N
60N
30N
EQ
30S
60S
90S
LATITUDE
ERBE
0 to −15
0 to −9
0 to −9 rad only

Figure 9

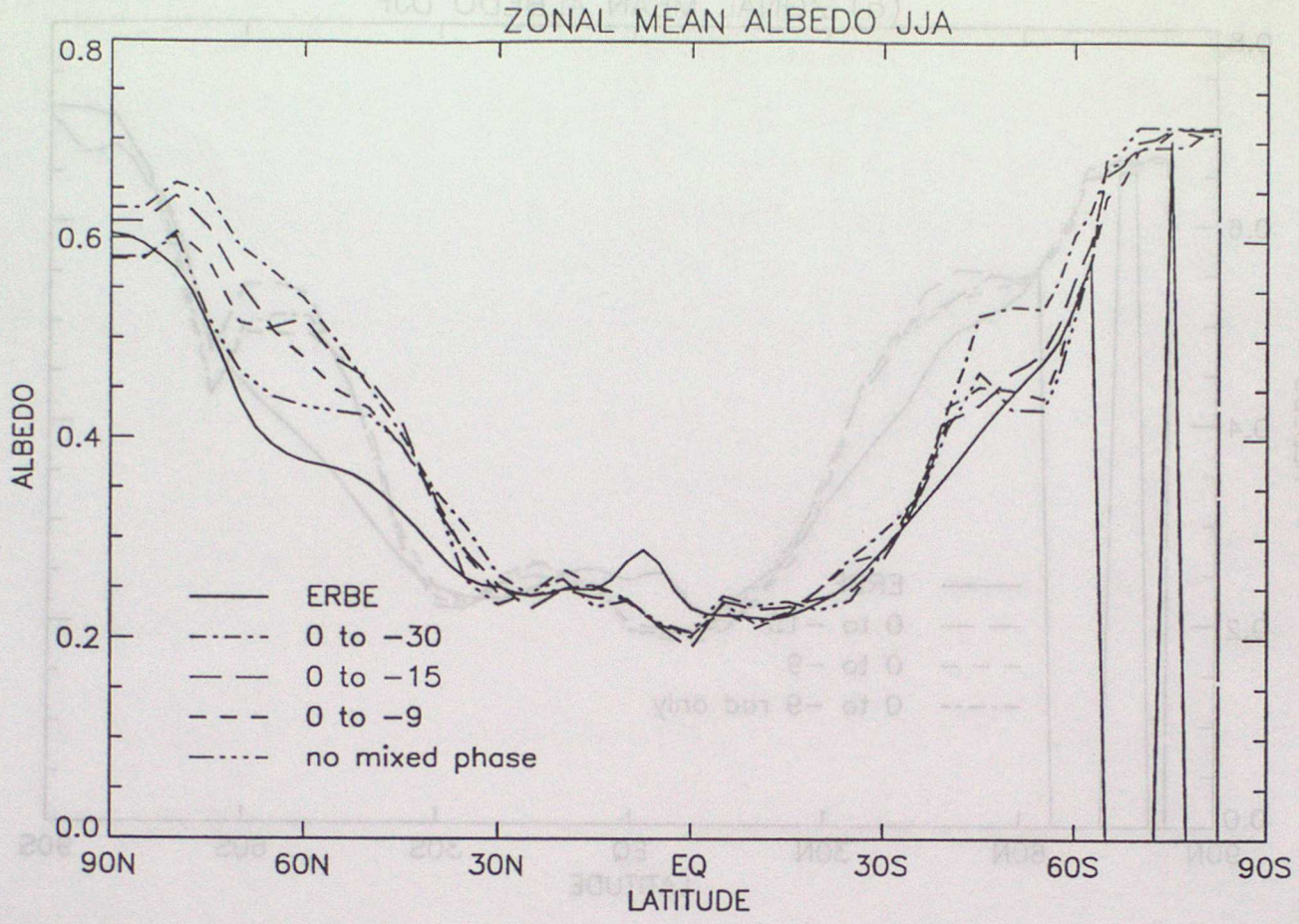

ZONAL MEAN ALBEDO JJA
ALBEDO
0.8
0.6
0.4
0.2
0.0
90N
60N
30N
EQ
30S
60S
90S
LATITUDE
ERBE
0 to −30
0 to −15
0 to −9
no mixed phase

Figure 10

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 1	Oct 1990	Estimates of the sensitivity of climate to vegetation changes using the Penman-Monteith equation. P R Rowntree
CRTN 2	Oct 1990	An ocean general circulation model of the Indian Ocean for hindcasting studies. D J Carrington
CRTN 3	Oct 1990	Simulation of the tropical diurnal cycle in a climate model. D P Rowell
CRTN 4	Oct 1990	Low frequency variability of the oceans. C K Folland, A Colman, D E Parker and A Bevan
CRTN 5	Dec 1990	A comparison of 11-level General Circulation Model Simulations with observations in the East Sahel. K Maskell
CRTN 6	Dec 1990	Climate Change Prediction. J F B Mitchell and Qing-cun Zeng
CRTN 7	Jan 1991	Deforestation of Amazonia - modelling the effects of albedo change. M F Mylne and P R Rowntree
CRTN 8	Jan 1991	The role of observations in climate prediction and research. D J Carson
CRTN 9	Mar 1991	The greenhouse effect and its likely consequences for climate change. D J Carson
CRTN 10	Apr 1991	Use of wind stresses from operational N.W.P. models to force an O.G.C.M. of the Indian Ocean. D J Carrington
CRTN 11	Jun 1991	A new daily Central England Temperature series, 1772-1991. D E Parker, T P Legg and C K Folland
CRTN 12	Jul 1991	Causes and predictability of Sahel rainfall variability. D P Rowell, C K Folland, K Maskell, J A Owen, M N Ward

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 13	Jul 1991	Modelling changes in climate due to enhanced CO2, the role of atmospheric dynamics, cloud and moisture. C A Senior, J F B Mitchell, H Le Treut and Z-X Li
CRTN 14	Sep 1991	Sea temperature bucket models used to correct historical SST data in the Meteorological Office. C K Folland
CRTN 15	Aug 1991	Modelling climate change, and some potential effects on agriculture in the U.K. P R Rowntree, B A Callander and J Cochrane
CRTN 16	Aug 1991	The Boreal Forests and Climate G Thomas and P R Rowntree
CRTN 17	Aug 1991	Development of a Stratosphere-Troposphere Data Assimilation System. R Swinbank.
CRTN 18	Sep 1991	A study of asynchronous coupling using a simple climate model. M K Davey.
CRTN 19	Sep 1991	The Oceanic Carbon Cycle. N K Taylor
CRTN 20	Nov 1991	Worldwide ocean-atmosphere surface fields in Sahel wet and dry years using provisionally corrected surface wind data. M N Ward
CRTN 21	Dec 1991	Coupled tropical ocean global atmosphere models at the UKMO. M K Davey, C Gordon, S Ineson and S Lawrence
CRTN 22	Dec 1991	Empirical parameterisation of tropical ocean-atmosphere coupling. M Allen, M K Davey, D L T Anderson and P D Killworth
CRTN 23	Feb 1992	The temporal evolution of Equatorial Currents in the Indian Ocean D L T Anderson, D J Carrington, R A Corry and C Gordon
CRTN 24	Feb 1992	Stratospheric analyses provided by the U.K. Meteorological Office M J Bailey, A O'Neill and V D Pope

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 25	Feb 1992	Modelling interannual variability in the Indian Ocean using momentum fluxes from the UKMO and ECMWF operational weather analyses. D L T Anderson and D J Carrington
CRTN 26	Mar 1992	A GCM simulation of the impact of Amazonian deforestation on climate using an improved canopy representation J Lean and P R Rowntree
CRTN 27	Mar 1992	The parameterization of rainfall interception in GCMs A J Dolman and D Gregory
CRTN 28	Jun 1992	Development of worldwide marine data eigenvectors since 1985 A W Colman
CRTN 29	Jun 1992	A tropical ocean model with reduced physics M K Davey
CRTN 30	Jun 1992	International Temperature Workshop, Boulder, Colorado, USA, 16 January 1992 Edited by D E Parker
CRTN 31	Jul 1992	Simulation of clear-sky outgoing longwave radiation over the oceans using operational analyses A Slingo and M J Webb
CRTN 32	Sep 1992	A prediction of the transient response of climate J M Murphy
CRTN 33	Nov 1992	LEPS scores for assessing climate model simulations and long-range forecasts. C K Folland
CRTN 34	Jan 1993	Stratospheric Data Assimilation System Guide Editer: R Swinbank
CRTN 35	Mar 1993	A Stratosphere-Troposphere Data Assimilation System R Swinbank and A O'Neill
CRTN 36	Mar 1993	Validation of hydrological schemes for climate models against catchment data. P R Rowntree and J Lean

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 37	Apr 1993	Modelling of palaeoclimates: Examples from the recent past J F B Mitchell
CRTN 38	May 1993	A simulation of seasonality in ENSO forecast skill M K Davey, D L T Anderson and S Lawrence
CRTN 39	Jul 1993	ENSO Prediction experiments using a simple ocean-atmosphere model D-H Wu, D L T Anderson and M K Davey
CRTN 40	Sep 1993	Diagnosis of dynamic sea-surface and sea-level changes from the Cox ocean model J M Gregory
CRTN 41	Sep 1993	Seasonal variations of the clear-sky greenhouse effect: the role of changes in atmospheric temperatures and humidities M J Webb, A Slingo and G L Stephens
CRTN 42	Nov 1993	Sea-level changes under increasing atmospheric CO_2 in a transient coupled ocean-atmosphere GCM experiment. J M Gregory
CRTN 43	Dec 1993	Global and regional patterns of climate change: recent predictions for the Arctic P R Rowntree
CRTN 44	Feb 1994	The effect of changing horizontal diffusion in the atmospheric version of the unified climate model C D Hall and R A Stratton
CRTN 45	Mar 1994	Simulation of El-Niño/Southern Oscillation like variability in a global AOGCM and its response to CO_2 increase. S F B Tett
CRTN 46	Apr 1994	Global data required for monitoring climate change. D E Parker and C K Folland
CRTN 47	May 1994	Seasonal uptake of anthropogenic CO_2 in an ocean general circulation model. N K Taylor

CLIMATE RESEARCH TECHNICAL NOTES

CRTN 48 Jun 1994 A tropic-wide oscillation of boreal summer rainfall and patterns of sea-surface temperature.
M N Ward, K Maskell, C K Folland, D P Rowell and R Washington

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